CERTS
Consortium for Electric Reliability Technology Solutions

CALIFORNIA ENERGY COMMISSION

Integration of Distributed Energy Resources

The CERTS MicroGrid Concept

CONSULTANT REPORT

OCTOBER 2003
P500-03-089F

Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

Prepared By:

CERTS Program Office
Lawrence Berkeley National Laboratory
20 Cyclotron Road,
MS90-4000
Berkeley, CA 94720

Contract No. 150-99-003

Prepared For:

Don Kondoleon,
Project Manager

Laurie ten-Hope,
PIER ProgramArea Lead

Terry Surles,
PIER Program Director

Robert L. Therkelsen,
Executive Director

Preface

The U.S. Electricity Grid Today The U.S. electric power system is in the midst of a fundamental transition from a centrally planned and utility-controlled structure to one that will depend on competitive market forces for investment, operations, and reliability management. Electricity system operators are being challenged to maintain the reliability of the grid and support economic transfers of power as the industry's structure changes and market rules evolve. Meanwhile, U.S. economy depends more than ever on reliable and high quality electricity supplies. New technologies are needed to prevent major outages such as those experienced on the Western grid on August 10, 1996, which left 12 million people without electricity for up to eight hours and cost an estimated $2 billion.

The Consortium for Electric Reliability Technology Solutions (CERTS) was formed in 1999 to research, develop, and disseminate new methods, tools, and technologies to protect and enhance the reliability of the U.S. electric power system and functioning of a competitive electricity market. CERTS is currently conducting research for the U.S. Department of Energy (DOE) Transmission Reliability Program and for the California Energy Commission (CEC) Public Interest Energy Research (PIER) Program. The members of CERTS include the Electric Power Group, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, the National Science Foundation's Power Systems Engineering Research Center, and Sandia National Laboratories.

LBNL-50829

Consortium for Electric Reliability Technology Solutions

White Paper on

Integration of Distributed Energy Resources

The CERTS MicroGrid Concept

Prepared for

Transmission Reliability Program
Office of Power Technologies
Assistant Secretary for Energy Efficiency and Renewable Energy
U.S. Department of Energy

Energy Systems Integration Program
Public Interest Energy Research
California Energy Commission

Prepared by

Robert Lasseter, Abbas Akhil, Chris Marnay, John Stephens,
Jeff Dagle, Ross Guttromson, A. Sakis Meliopoulous, Robert Yinger, and Joe Eto

April 2002

The work described in this report was coordinated by the Consortium for Electric Reliability Technology Solutions, and funded by the Assistant Secretary of Energy Efficiency and Renewable Energy, Office of Power Technologies of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and by the California Energy Commission, Public Interest Energy Research Program, under Work for Others Contract No. BG 99-39.

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1. Introduction

Evolutionary changes in the regulatory and operational climate of traditional electric utilities and the emergence of smaller generating systems such as microturbines have opened new opportunities for on-site power generation by electricity users. In this context, distributed energy resources (DER) - small power generators typically located at users' sites where the energy (both electric and thermal) they generate is used - have emerged as a promising option to meet growing customer needs for electric power with an emphasis on reliability and power quality. The portfolio of DER includes generators, energy storage, load control, and, for certain classes of systems, advanced power electronic interfaces between the generators and the bulk power provider. This white paper proposes that the significant potential of smaller DER to meet customers' and utilities' needs can be best captured by organizing these resources into MicroGrids[1].

> ***The Consortium for Electric Reliability Technology Solutions (CERTS) MicroGrid concept assumes an aggregation of loads and microsources operating as a single system providing both power and heat. The majority of the microsources must be power electronic based to provide the required flexibility to insure operation as a single aggregated system. This control flexibility allows the CERTS MicroGrid to present itself to the bulk power system as a single controlled unit that meets local needs for reliability and security***.

The CERTS MicroGrid represents an entirely new approach to integrating DER. Traditional approaches for integrating DER focus on the impacts on grid performance of one, two, or a relatively small number of microsources. An example of the traditional approach to DER is found in the Institute of Electrical and Electronics Engineers (IEEE) Draft Standard P1547 for Distributed Resources Interconnected with Electric Power Systems. This standard focuses on ensuring that interconnected generators will shut down automatically if problems arise on the grid. By contrast, the CERTS MicroGrid would be designed to seamlessly separate or island from the grid and, reconnecting to the grid once they are resolved.

A critical feature of the CERTS MicroGrid derives from its presentation to the surrounding distribution grid as a single self-controlled entity; that is, it appears to the grid as indistinguishable from other currently legitimate customer sites. Maintaining this profile relies on the flexibility of advanced power electronics that control the interface between microsources and their surrounding AC system. In other words, the CERTS MicroGrid concept eliminates dominant existing concerns and the consequent approaches for integrating DER. Current

[1] The key feature of candidate DER generating technologies for use by the CERTS MicroGrid concept is their interconnection through inverter-like power electronics, and not any particular rated kW power capacity. For pragmatic reasons of availability and controllability this CERTS effort is initially focused on microturbines and assumes their size is less than 500 kW. However, fuel cells and other emerging technologies that might ultimately be used in MicroGrids could be larger. The role that MicroGrids can play as elements of larger power parks whose total installed capacity is measures in the 10's of MW is also illustrated.

attention tends to focus on assessing how many DER can be *tolerated* before their collective electrical impact begins to create problems, such as excessive current flows following faults and voltage fluctuations. The MicroGrid architecture insures that its electrical impact on its bulk power provider at least qualifies it as a *good citizen*; that is, it complies with grid rules and does no harm beyond what would be acceptable from an existing customer. Given attractive remuneration, the MicroGrid could provide interruptible load. Although technical barriers discourage it, the MicroGrid could serve as a small source of power or ancillary services, thereby potentially making it a *model citizen*. The benefits it could offer to the distribution system are congestion relief, postponement of new generation or delivery capacity, response to load changes and local voltage support.

From the grid's perspective, the central advantage of a MicroGrid is that it can be regarded as a controlled entity within the power system that can be operated as a single aggregated load. In other words, it can establish binding contractual agreements with the bulk power provider covering its pattern of usage that are at least as strict as those covering existing customers, and it potentially it could provide additional services.

Customers benefit from a MicroGrid because it is designed and operated to meet their local needs for heat and power as well as provide uninterruptible power, enhance local reliability, reduce feeder losses, and support local voltages/correct voltage sag. The pattern of exchange of energy services between the MicroGrid and the bulk power provider grid is determined by prevailing economic conditions.

This white paper explores key technical issues raised by the MicroGrid concept. Background and contextual information relevant to MicroGrids is presented in Section 2.0, which briefly describes generation technologies implementable in MicroGrids and the particular role that combined heat and power could play in MicroGrids. Section 3.0 describes MicroGrid design and operation in detail. Key technical challenges associated with MicroGrids are delineated in the next three sections - their presentation to the bulk power provider grid (Section 4.0), controls required for them to function effectively both in connection to the bulk power provider grid and in isolation (or islanded) from the grid (Section 5.0), protection and safety issues that must be addressed (Section 6.0). Section 7.0 discusses some fundamental economic questions that will ultimately dictate the configuration and operation of the MicroGrid. Section 8.0 summarizes the issues presented in the paper and highlights areas of needed research. Appendices A-D examine in detail the background and contextual issues related to MicroGrids: generation technologies, electrical issues, and environmental and regulatory constraints.

2. Background

2.1 Technologies

As discussed earlier, the key feature that makes the MicroGrid possible is the power electronics, control, and communications capabilities that permit a MicroGrid to function as a semiautonomous power system. The power electronics are the critical distinguishing feature of the MicroGrid, and they are discussed in detail below. This section describes some of the other technologies whose development will shape MicroGrids. While the more familiar reciprocating engines will likely remain competitive in many applications for the foreseeable future, they lack power electronics therefore minimizing their role in MicroGrids. Widespread use of fuel cells, particularly high temperature ones most interesting for combined heat and power (CHP) applications, remains a few years away. Among the renewable technologies, medium to large photovoltaic systems, possibly building integrated, are a particularly promising technology, while other renewables may also play a role. In addition to generating technologies, MicroGrids also include storage, load control and heat recovery equipment.

Microturbines, currently in the 25-100 kW range, although larger ones are under development, may ultimately be mass-produced at low cost. These are mechanically simple, single shaft devices, using high-speed (50,000-100,000 rpm) typically with airfoil bearings. They are designed to combine the reliability of commercial aircraft auxiliary power units (APU's) with the low cost of automotive turbochargers. Despite their mechanical simplicity, microturbines rely on power electronics to interface with loads. Example products include: Capstone's 30-kW and 60-kW systems, the former Honeywell 75-kW Parallon machine, and products from European manufacturers Bowman and Turbec that feature CHP capabilities. Microturbines should also be acceptably clean running. Their primary fuel is natural gas, although they may also burn propane or liquid fuels in some applications, which permits clean combustion, notably with low particulates.

Fuel cells are also well suited for distributed generation applications. They offer high efficiency and low emissions but are currently expensive. Phosphoric acid cells are commercially available in the 200-kW range, and high temperature solid-oxide and molten-carbonate cells have been demonstrated and are particularly promising for MicroGrid application. A major development effort by automotive companies has focused on the possibility of using on-board reforming of gasoline or other common fuels to hydrogen, to be used in low temperature proton exchange membrane (PEM) fuel cells. Fuel cell engine designs are attractive because they promise high efficiency without the significant polluting emissions associated with internal combustion engines. Many other major companies are investing in PEM fuel cells for mobile applications, and the recently announced Bush administration FreedomCAR Initiative should accelerate development. This will accelerate PEM development relative to other fuel cells, should lower costs, and will partially compensate for the relatively unattractiveness of low-temperature PEMs for CHP applications. Higher temperature PEMs are also under development.

Renewable generation could appear in MicroGrids, especially those interconnected through power electronic devices, such PV systems or some wind turbines. Biofueled microturbines are also a possibility. Environmentally, fuel cells and most renewable sources are a major improvement over conventional combustion engines.

Storage technologies, such as batteries, and ultracapacitors are important components of MicroGrids. Storage on the microsource's dc bus provides ride-through capabilities during system changes. Storage systems have become more versatile than they were five years ago. Twenty eight-cell ultracapacitors can provide up to 12.5 kW for a few seconds.

Heat recovery technologies for use in CHP systems are necessary for MicroGrid viability, as is explained in the following section. Many of these technologies are relatively developed and familiar, such as low and medium temperature heat exchangers. Others, such as absorption chillers, are known but not in widespread use.

Environmentally, fuel cells and most renewable sources are a major improvement over conventional combustion engines. Microturbines should also be acceptably clean running. Their primary fuel will be natural gas, although they may also burn propane or liquid fuels in some applications, which permits clean combustion, notably with low particulates. NOx emissions, which are a precursor to urban smog, are mainly a consequence of combustion. Some traditional combustion fuels, notably coal, contain nitrogen that is oxidized during the combustion process, but even burning fuels that contain no nitrogen emits NOx, which forms at high combustion temperatures from the nitrogen and oxygen in the air. Gas turbines, reciprocating engines, and reformers all involve high temperatures that result in NOx production. These devices must be carefully designed to limit NOx formation. Thermal microsources that effectively use waste heat can also have low overall carbon emissions that compete with those of modern central station combined-cycle generators. Human exposure to smog also depends on the location of smog precursor emissions. Since DER is likely to move NOx emissions closer to population centers, exposure patterns will be affected.

Finally, it should be recognized that many of the MicroGrid technologies will be fueled by natural gas, at least initially, and expanded use of DER will require added natural gas delivery infrastructure, some of it preferably at high pressure to serve microturbines.

2.2 Combined Heat and Power (CHP)

One important potential benefit of MicroGrids is an expanded opportunity to utilize the waste heat from conversion of primary fuel to electricity. Because typically half to three-quarters of the primary energy consumed in power generation is ultimately released unutilized to the environment, the potential gains from using this heat productively are significant.

The gains of increased conversion efficiency are threefold. First, fuel costs will be reduced both because individual fuel purchases will decrease and constrained overall demand will drive down fuel prices. Second, carbon emissions will be reduced. And, third, the environmental problem of disposing of large power plant waste heat into the environment will diminish. The emergence and deployment of technologies to facilitate efficient local use of waste heat is, therefore, key for MicroGrids to emerge as a significant contributor to the national electricity supply.

Use of waste heat in grid scale CHP systems is more common in many economies than in the U.S. where it is typically only found in industrial facilities. For example, in Denmark as of 1996, CHP plants met 48 percent of the domestic electricity demand and 38 percent of the domestic heat demand. This level of CHP contribution is believed to reduce CO_2 emissions by approximately 7-10 Mt per year, or more than 10 percent of the total CO_2 emissions of the country, relative to estimated emissions if heat and power were produced separately. Most of the heat capture that enables such impressive results is achieved in medium-sized systems that are at larger scales than MicroGrids. However, some European countries, notably The Netherlands, have made significant progress towards developing smaller, i.e. kW scale, CHP applications, such as greenhouse heating.

Unlike electricity, heat, usually in the form of steam or hot water, cannot be easily or economically transported long distances, so CHP systems typically provide heat for industrial processes, on-site space heating, local district heating, or for domestic hot water or sterilization. To make CHP systems viable, a sufficiently large need for heat must exist within a sufficiently dense area that circulation of steam, hot water, or another appropriate medium is feasible and economic. Given that space cooling and refrigeration are both significant consumers in the U.S., application of absorption cooling and/or desiccant dehumidification could be a highly attractive feature of MicroGrids. These are key enabling technologies for MicroGrids and DER generally.

MicroGrids can capture two significant potential advantages over existing larger scale CHP systems:

1. The production of heat can move closer to the point of use. In an extreme example, fuel cells could be placed on every floor of a hospital to meet each floor's hot water needs. Because electricity is more readily transported than heat, generation of heat close to the location of the heat load will usually make more sense than generation of heat close to the electrical load, and the MicroGrid permits generators to be placed optimally in relation to heat loads.

2. The scale of heat production for individual units is small and therefore offers greater flexibility in matching to heat requirements. A MicroGrid could be constructed from the most economic combination of waste-heat-producing generators and non-waste-heat producing generators so that the combined generation of electricity and heat is optimized. Against these advantages, the possible non-coincidence of electricity and heat requirements will pose a significant handicap in many situations. Further, systems must be flexible for changing patterns of use, especially because small businesses have short average life spans.

2.3 Interconnection Issues

Local interconnection standards vary considerably from one bulk power provider to the next. A national standard, ANSI standard P1547 (Draft) Standard for Distributed Resources Interconnected with Electric Power Systems is being drafted by the IEEE SCC21 working group. This standard rests on certain assumptions about the contribution of DER to power quality and system reliability. Although P1547 does not use the term MicroGrid, it allows for implementation of a group of DER, which it refers to as a Local Electric Power System (LEPS). The standard applies at the point where a LEPS or MicroGrid connects to the grid and is related to the aggregate DER rating within the MicroGrid. In other words, the rules applied to a MicroGrid containing many small DER devices would be the same as for one large DER. However, the applicability of P1547 is limited to a DER rating of 10 MVA, which is larger than the ratings expected for MicroGrids.

3. MicroGrid Structure

The MicroGrid structure assumes an aggregation of loads and microsources operating as a single system providing both power and heat. The majority of the microsources must be power electronic based to provide the required flexibility to insure controlled operation as a single aggregated system. This control flexibility allows the MicroGrid to present itself to the bulk power system as a single controlled unit, have plug-and-play simplicity for each microsource, and meet the customers' local needs. These needs include increased local reliability and security.

Key issues that are part of the MicroGrid structure include the interface, control and protection requirements for each microsource as well as MicroGrid voltage control, power flow control, load sharing during islanding, protection, stability, and over all operation. The ability of the MicroGrid to operate connected to the grid as well as smooth transition to and from the island mode is another important function.

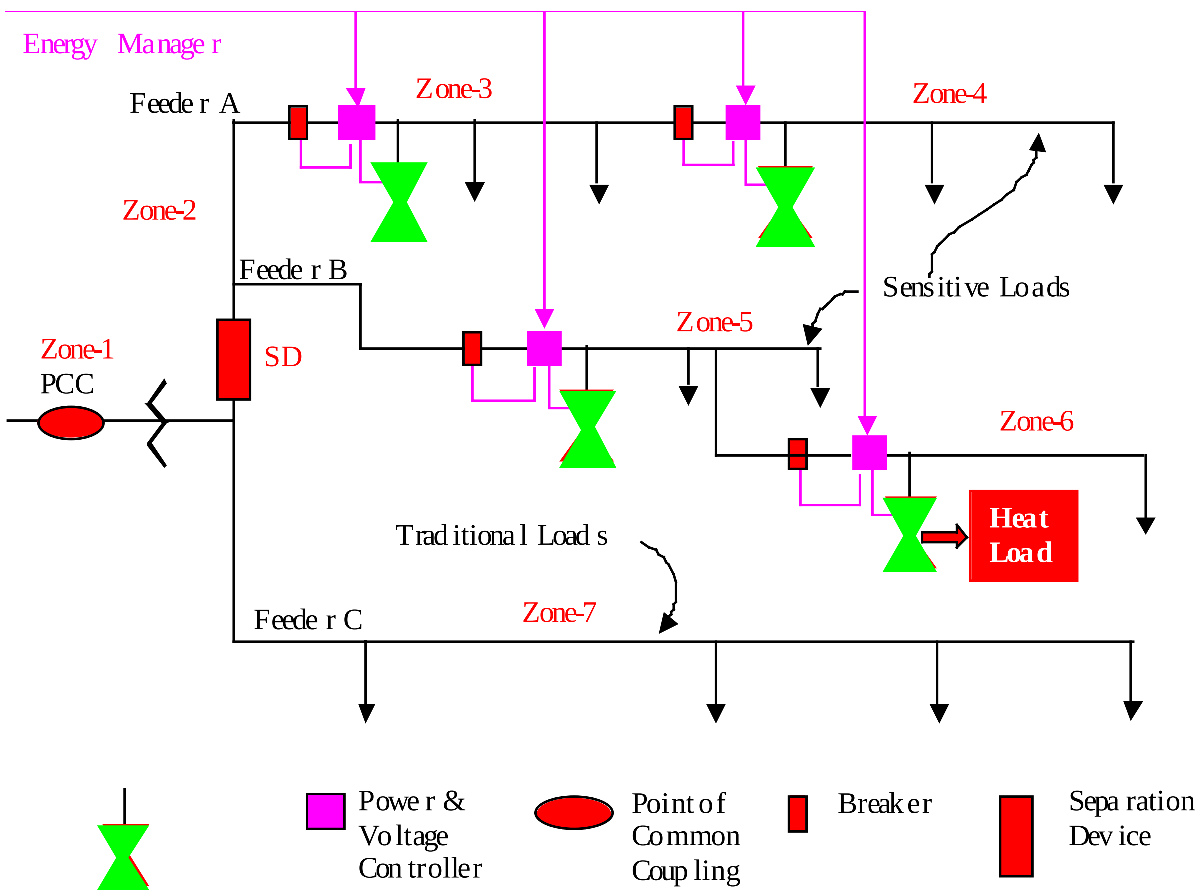


Figure 3.1 MicroGrid Architecture

Figure 3.1 illustrates the basic MicroGrid architecture. The electrical system is assumed to be radial with three feeders – A, B, and C – and a collection of loads. The microsources are either microturbines or fuel cells interfaced to the system through power electronics. The Point of Common Coupling (PCC) is on the primary side of the transformer and defines the separation between the grid and the MicroGrid. At this point the MicroGrid must meet the prevailing interface requirements, such as defined in draft standard IEEE P1547.

The sources on Feeder A & B allow full exploration of situations where the microsources are placed away from the common feeder bus to reduce line losses, support voltage and/or use its waste heat. Multiple microsources on a radial feeder increase the problem of power flow control and voltage support along the feeder when compared to all sources being placed at the feeder's common bus, but this placement is key to the plug-and-play concept. The feeders are usually 480 volts or smaller. Each feeder has several circuit breakers and power and voltage flow controllers. The power and voltage controller near each microsource provides the control signals to the source, which regulates feeder power flow and bus voltage at levels prescribed by the Energy Manager. As downstream loads change, the local microsource's power is increased or decreased to hold the total power flow at the dispatched level.

In Figure 3.1 there are two feeders with microsources and one without any generation to illustrate a wide range of options. During disturbances on the bulk power system Feeders A & B can island using the separation device (SD) to minimize disturbance to the sensitive loads. Of course islanding does not make sense if there is not enough local generation to meet the demands of the sensitive loads. The traditional loads on Feeder C are left to ride through the disturbance. This eliminates nuisance trips of the traditional load when the MicroGrid islands to protect critical loads.

The MicroGrid assumes three critical functions that are unique to this architecture:

- **Microsource Controller**. The Power and Voltage Controller coupled with the microsource provide fast response to disturbances and load changes without relying on communications.
- **Energy Manager**. Provides operational control through the dispatch of power and voltage set points to each Microsource Controller. The time response of this function is measured in minutes.
- **Protection**. Protection of a MicroGrid in which the sources are interfaced using power electronics requires unique solutions to provide the required functionality.

3.1 Microsource Controller

The basic operation of the MicroGrid depends on the Microsource Controller to; regulate power flow on a feeder as loads on that feeder change their operating points; regulate the voltage at the interface of each microsource as loads on the system change; and insure that each microsource rapidly picks up its share of the load when the system islands. In addition to these control functions the ability of the system to island smoothly and to automatically reconnect to the bulk power system is another important operational function. Most of this set of key functions does not exist on currently available microsources.

Another important feature of each Microsource Controller is that it responds in milliseconds and uses locally measured voltages and currents to control the microsource during all system or grid events. Fast communication among microsources is not necessary for MicroGrid operation; each inverter is able to respond to load changes in a predetermined manner without data from other sources or locations. This arrangement enables microsources to "plug and play" – that is, microsources can be added to the MicroGrid without changes to the control and protection of units that are already part of the system. The basic inputs to the Microsource Controller are steady-state set points for power, P, and local bus voltage, V. Section 5.0 discusses Microsource Controller in more detail.

3.2 Energy Manager

The Energy Manager provides for system operation of the MicroGrid through dispatch of power and voltage set points to each Microsource Controller. This function could be as simple as having a technician enter these set points by hand at each controller to a state-of-the-art communication system with artificial intelligence. The actual values of dispatch of P and V depends on the operational needs of the MicroGrid. Some possible criteria are:

- Insure that the necessary heat and electrical loads are met by the microsources;
- Insure that the MicroGrid satisfies operational contracts with the bulk power provider;
- Minimize emissions and/or system losses;
- Maximize the operational efficiency of the microsources; and
- et cetera

3.3 Protection

The protection coordinator must respond to both system and MicroGrid faults. For a fault on the grid, the desired response may be to isolate the critical load portion of the MicroGrid from the grid as rapidly as is necessary to protect these loads. This provides the same function as an uninterruptible power supply at a potentially lower incremental cost. The speed at which the MicroGrid isolates from the grid will depend on the specific customer loads on the MicroGrid. In some cases, sag compensation can be used to protect critical loads without separation from the distribution system. If a fault occurs within the islandable portion of the MicroGrid, the desired protection is to isolates the smallest possible section of the radial feeder to eliminate the fault. For example a fault in Zone-4, Figure 3.1, could be detected using differential current sensing at the closest Power & Voltage Controller resulting in the operation of the adjacent breaker to isolate the fault with minimum disturbance to the rest of the MicroGrid. Further discussion of the functioning of the protection system is found in Section 6.0.

3.4 Large Systems-Interconnected MicroGrids – Power Parks

Because a MicroGrid exploits low voltage, use of waste heat, and the flexibility of power electronics, its practical size may be limited to a few MVA (even though IEEE draft standard P1547 specifies an upper limit of 10MVA). In a large complex, loads could be divided into many controllable units e.g., among buildings or industrial sites. Each unit could be supplied by one or more MicroGrids connected through a distribution system.

For example, consider a power park with a total load in excess of 50 MVA. This system could be supplied from the transmission system through one or two substations using 13.8-kV underground cables. Each load group (heat and/or electrical) would be a MicroGrid connected to the 13.8-kV supply. In addition to these MicroGrids, the power park could employ larger generation such as one- to ten-MVA gas turbines directly connected to the 13.8-kV feeder. Each MicroGrid would be a dispatchable load. The power park controls would provide each MicroGrid with its load level (drawing power from the 13.8-kV feeder) while the gas turbines P and Q/V would be dispatched either locally or by the bulk power producer. The advantages of this system are that the MicroGrid structure insures greater stability and controllability, allows for a distributed command and control system, and provides redundancy to insure greater power supply reliability for the power park.

4. MicroGrid Presentation to the Grid

The MicroGrid must connect to the grid without compromising grid reliability or protection schemes or causing other problems, consistent with the minimal standards for all connected devices. However, the MicroGrids can offer more value to the grid than simply meeting a *doing-no-harm* standard i.e. being a *good citizen* of the grid. MicroGrids can benefit the grid by reducing congestion and other threats to system adequacy if they are deployed as interruptible, or controlled loads that can be partially shed as necessary in response to changing grid conditions. Furthermore, the power electronics in a MicroGrid could also be designed so it behaves like a constant impedance load, a modulated load, or a dispatchable load, to list a few. In addition, MicroGrids could provide local premium power and ancillary services, such as local voltage support, although the low voltage limits its ability to feed into the grid. If the MicroGrid had such features it could be considered a *model citizen* of the grid.

4.1 Load as a Resource

The CERTS MicroGrid can be thought of as a controlled cell of the power system within which heat and power are generated for local customers, and generation and load are controlled. Because joint control of on-site generation, storage, and loads is fundamental to the MicroGrid, grid load could be shed by it in response to system needs. The MicroGrid also could contract to provide firm levels of energy and ancillary services. That is, if schedules permit, the MicroGrid could reduce its load on the grid either by raising the share it generates to meet its own loads or by reducing its load. If the value of the MicroGrid presenting itself as a dispatchable load were taken into account when MicroGrid equipment was installed, essential load-shedding capabilities could be built into the system.

Traditional load shedding has been in the form of interruptible contracts or tariffs.[2] Typically, a customer agrees to be curtailed up to an agreed number of times and durations. The customer's reward is either a reduced energy rate that lowers the customer's overall energy bill or a capacity and/or energy payment on the actual load being placed at risk of interruption. Usually,

[2] Load As a Reliability Resource in the Restructured Electricity Market. J. Kueck, B. J. Kirby, J.Eto,, R. H. Staunton, C. Goldman, C. Marnay, C. Martinez. June, 2001.

customers are notified by phone, fax, or mobile text messaging, when their service must be interrupted, and verification that the customer load was shed as requested takes place *ex post* based on meter data. A customer can choose not to comply with the direction to shed load although penalties are often levied for non-compliance and may be severe. A MicroGrid could easily participate in this type of load-shedding program. In some load-curtailment programs, loads are interrupted immediately and without warning. In New Zealand, for example, large numbers of loads have agreed to the installation of under-frequency relays that enable extremely rapid curtailment. A MicroGrid could participate in a similar program if it had the capability to respond by rapidly drawing down storage then increasing its self-generation or reducing its load.

Joint, local control of generation and load is at the heart of the MicroGrid concept, which gives a particular meaning to demand-side management. Rather than controlling load for the purpose of adjusting its profile to benefit the wider power system, the MicroGrid controls generation and load together to meet the objectives of MicroGrid customers as economically as possible, which might include participation in interruptible load programs. The key issue for grid reliability is how to offer incentives to MicroGrids to invest and behave in a fashion that enhances grid reliability: e.g., real time pricing or contracts/rate discount options for load curtailment. Load shedding that takes place more rapidly than the electricity commodity market can respond to system conditions (e.g. load curtailment) is a particularly important service that the MicroGrid could offer.

4.2 Dynamic Interactions

DER applications are sufficiently small in number at this point so their influence on the stability of the high-voltage transmission system is not an issue. However, if DER become more common, they could have a substantial influence on grid stability. Undesirable dynamic interactions could cause key, heavily loaded transmission lines to trip, interrupting power exports and imports between areas. However, if MicroGrids are designed with their dynamic impact on the transmission system taken into account, they can enhance the stability of transmission lines, which could permit transmission power limits to increase. The question of how much penetration of DER the grid can handle before stability problems result is a not an issue with MicroGrids because they are designed to satisfy their predetermined local load without creating any stability problems for the transmission system.

5. Control Methods for MicroGrids

Power electronics can provide the control and flexibility for the MicroGrid to meet its customers' as well as the grid's needs. MicroGrid controls need to insure that: new microsources can be added to the system without modification of existing equipment, the MicroGrid can connect to or isolate itself from the grid in a rapid and seamless fashion, reactive and active power can be independently controlled, voltage sag and system imbalances can be corrected, and that the MicroGrid can meet the grid's load dynamics requirements.

Microsource Controller techniques described below rely on the inverter interfaces found in fuel cells, microturbines, and storage technologies. A key element of the control design is that communication among microsources is unnecessary for basic MicroGrid operation. Each Microsource Controller must be able to respond effectively to system changes without requiring data from other sources or locations.

5.1 Microsource Control Functions

Operation of the MicroGrid assumes that the power electronic controls of current microsources are modified to provide a set of key functions, which currently do not exist. These control functions include the ability to: regulate power flow on feeders; regulate the voltage at the interface of each microsource; ensure that each microsource rapidly pickups up its share of the load when the system islands. In addition to these control functions the ability of the system to island smoothly and automatically reconnect to the bulk power system is another important operational function.

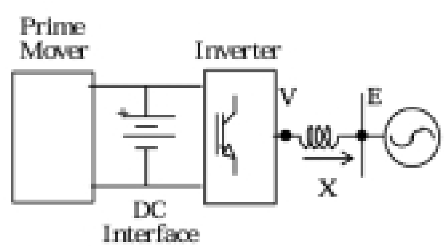


Figure 5.1 Interface Inverter System

Basic Control of Real and Reactive Power

There are two basic classes of microsources: DC sources, such as fuel cells, photovoltaic cells, and battery storage; and high-frequency AC sources such as microturbines, which need to be rectified. In both cases, the DC voltage that is produced is converted using a voltage source inverter. The general model for a microsource is shown in Figure 5.1. It contains three basic elements: prime mover, DC interface, and voltage source inverter. The microsource couples to the MicroGrid using an inductor. The voltage source inverter controls both the magnitude and phase of its output voltage, V. The vector relationship between the inverter voltage, V, and the local MicroGrid voltage, E, along with the inductor's reactance, X, determines the flow of real and reactive power (P &Q) from the microsource to the MicroGrid. The P & Q magnitudes are coupled as shown in the equations below. For small changes, P is predominantly dependent on the power angle, δ_p, and Q is dependent on the magnitude of the inverter's voltage, V. These relationships constitute a basic feedback loop for the control of output power and bus voltage, E, through regulation of reactive power flow.

$$P = \frac{3}{2}\frac{VE}{X}\sin\delta_p$$
$$Q = \frac{3}{2}\frac{V}{X}(V - E\cos\delta_p)$$
$$\delta_p = \delta_V - \delta_E$$

Voltage Regulation through Droop

Integration of large numbers of microsources into a MicroGrid is not possible with basic P-Q controls; voltage regulation is necessary for local reliability and stability. Without local voltage control, systems with high penetrations of microsources could experience voltage and/or reactive power oscillations. Voltage control must insure that there are no large circulating reactive currents between sources. The issues are identical to those involved in control of large synchronous generators. In the power grid, the impedance between generators is usually large enough to greatly reduce the possibility of circulating currents. However, in a MicroGrid, which is typically radial, the problem of large circulating reactive currents is significant. With small errors in voltage set points, the circulating current can exceed the ratings of the microsources.

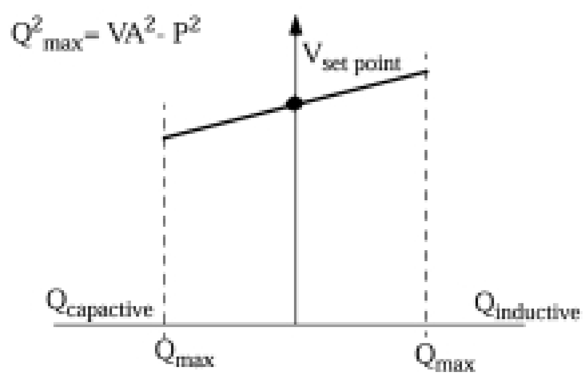


Figure 5.2 Voltage Set Point with Droop

This situation requires a voltage vs. reactive current droop controller so that, as the reactive current generated by the microsource becomes more capacitive, the local voltage set point is reduced. Conversely, as the current becomes more inductive, the voltage set point is increased. The function of the basic controller is shown in Figure 5.2. The Q limit shown in the figure is a function of the volts-ampere (VA) rating of the inverter and the power provided by the prime mover.

Fast Load Tracking and the Need for Storage

A MicroGrid with clusters of microsources and storage could be designed to operate both in isolation and connected to the power grid. When the MicroGrid operates in isolation, load-tracking problems will arise because microturbines and fuel cells respond slowly (time constants range from 10 to 200 seconds) and are inertia-less. Grid power systems currently have storage in the form of generators' inertia. When a new load comes on line, the initial energy balance is satisfied by the system's inertia, which results in a slight reduction in system frequency. A MicroGrid cannot rely on generator inertia and must provide some form of storage to insure initial energy balance.

MicroGrid storage can come in several forms: batteries or supercapacitors on the DC bus for each microsource; direct connection of AC storage devices (batteries, flywheels etc.); or use of traditional generation with inertia along with microsource generators. For the basic MicroGrid discussed in this paper it is assumed that there is adequate total storage on microsource dc buses to decouple prime mover time delay from the load. If the MicroGrid is not required to operate in island mode, the energy imbalance can be met by the AC system, and storage on the MicroGrid is not necessary.

Frequency Droop for Power Sharing (in Islanded Mode of Operation)

MicroGrids can provide premium power functions using control techniques where the MicroGrid can island smoothly and automatically reconnect to the bulk power system, much like a UPS system.

In island mode, problems such as slight errors in frequency generation at each inverter and the need to change power-operating points to match load changes must be addressed. Power vs. frequency droop functions at each microsource can take care of the problems without the need for a complex communication network.

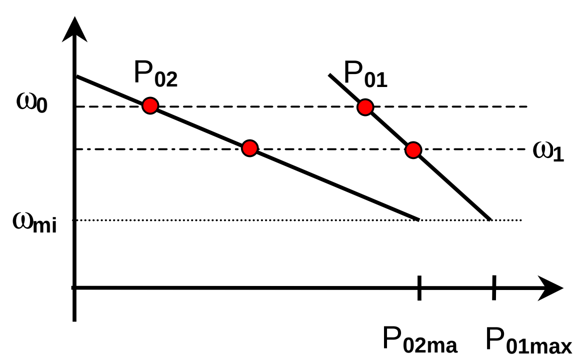


Figure 5.3 Power vs. Frequency Droop Control

When the MicroGrid is connected to the grid, MicroGrid loads receive power both from the grid and from local microsources, depending on the customer's situation. If the grid power is lost because of voltage drops, faults, blackouts, etc., the MicroGrid can transfer smoothly to island operation. When the MicroGrid separates from the grid, the voltage phase angles at each microsource in the MicroGrid change, resulting in an apparent reduction in local frequency. This frequency reduction coupled with a power increase allows for each microsource to provide its proportional share of load without immediate new power dispatch from the Energy Manager.

Consider two microsources as in Figure 5.3. In this example, the sources are assumed to have different ratings, P_{1max}, and P_{2max}. The dispatched power in grid mode (P_{01} and P_{02}) is defined at base frequency, ω_0. The droop is defined to insure that both systems are at rated power at the same minimum frequency.

During a change in power demand, these two sources operate at different frequencies, which cause a change in the relative power angles between them. When this change occurs, the two frequencies tend to drift toward a lower, single value for ω_1. Unit 2 was initially operating at a lower power level than Unit 1. However, at the new power level, Unit 2 has increased its share of the total power needs. Because droop regulation decreases the MicroGrid frequency a restoration function must be included in each controller. Droop control design is based on each microsource having a maximum power rating. As a consequence, droop is dependent on the dispatched power level while the microsources are connected to the grid.

5.2 Example System

An industrial plant with high motor loads can be used to illustrate the dynamics of the MicroGrid controls presented in the previous section. This industrial site has nearly 1.6 MW of motor load with motors ranging from 50 to 150 hp each; there are also two large synchronous machines. A 120-kV line provides power through a long 13.8-kV feeder consisting of overhead lines and underground cables. The plant has three main feeders; two at 480V and one at 2.4kV. The loads on the 480-V feeders are critical and must continue to be served if grid power is lost.

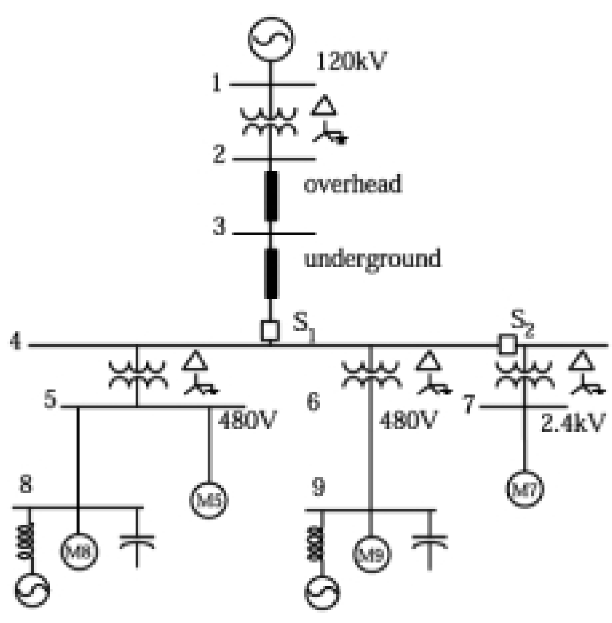


Figure 5.4 Example System, One-Line

Details of the plant are shown in Figure 5.4. The induction machine clusters (M8 and M9) are connected to buses 8 and 9 with capacitive voltage support. The machines are modeled as fixed loads with a pf = 0.85. The only dynamics in this model are the power electronics, their controls and the switching events. Two clusters of microsources are also connected to buses 8 and 9 to provide power and voltage support. In the absence of locally generated power, the voltages of buses 8 and 9 are 0.933 and 0.941 per unit (pu, on 480-V base) respectively. Total losses are 70 kW. Each cluster of microsources is rated at 600 KVA and provides both power injection and local voltage support. The microsource power injection is approximately one half the total power. With these sources operating, the voltages on buses 8 and 9 are regulated at 1 pu, and the total losses drop to 6kW, a reduction of 64kW.

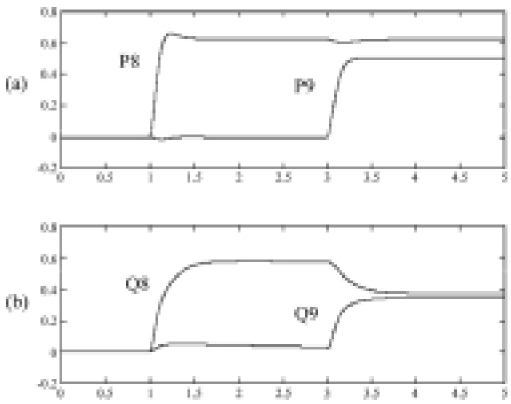


Figure 5.5 Start-up P & Q of Microsources in Grid-Connected Mode (a) Active Power, (b) Reactive Power

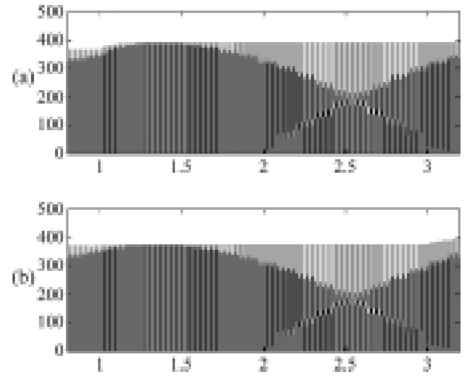


Figure 5.6 Regulated voltage (a) bus 8 (b) bus 9

Simulation of grid-connected operation is shown in Figures 5.5 and 5.6. In the initial state, local sources are not generating power, so Figure 5.5 shows zero real and reactive power injection and reduced voltages on buses 8 and 9. At t = one second, the generators at bus 8 are brought on line with a power setting of 446 kW and local voltage control. Note the voltage correction in Figure 5.6(a).

At t = three seconds, the units at bus 9 are brought on line with a power set point of 360 kW and local voltage control. Figure 5.5 shows the active and reactive power injections at the buses where units are located. As the second microsource is brought on line, the Q injection at bus 8 to maintain local voltage magnitude drops. Figure 5.6 shows half of the voltage envelope at the regulated buses during the start-up sequence. Voltage on bus 9 is controlled to 1 pu within a few cycles.

This example can also be used to simulate island operation with power sharing through droop. It is assumed that the ratings of the microsources are not adequate to supply the total load. The two 480-V feeders supply critical loads, and the M7 load on bus 7 can be dropped using breaker S_2 (see Figure 5.4)

At t=10 seconds, the MicroGrid moves from grid-connected to island operation by the tripping of switch S_1 in response to supply problems (Figure 5.7c). At the same time, the non-critical feeder is dropped using S_2. Waveforms for bus 8 and 9 voltages during the switch to island mode are shown in Figures 5.7(a)-(b). There is only a slight change from the sinusoidal steady state; the change lasts less than a cycle

Figure 5.8 shows the changes in active and reactive power during the transition. The microsources need to take up the loss of grid power. Both machine clusters increase their power injection as expected from the design of the droop characteristics. The machine with lighter load (Figure 5.3.) at bus 9 increases its output by 56% while the machine on bus 8 increases by 32% to meet the new load demands (see Figure 5.8(a)). Reactive power injection is reduced by 48%, but holds the voltages at 1 pu. Power regulation takes place very rapidly, and steady-state power is restored in fractions of a second.

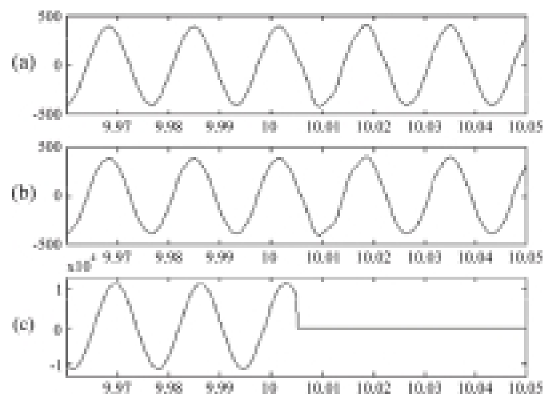


Figure 5.7 Regulated voltages during transfer to island operation (a) bus 8 (b) bus 9 (c) 13.8-kV feeder

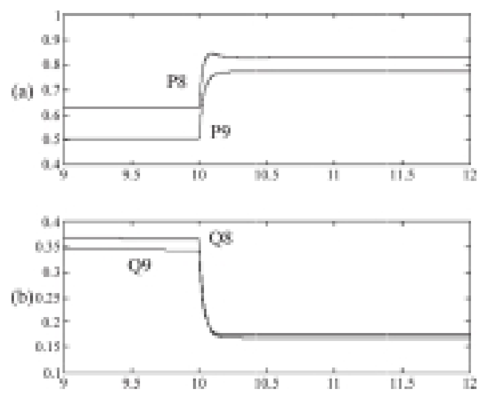


Figure 5.8 P&Q Transient during Transition from Grid-Connected to Island Operation

6. Protective Relaying and MicroGrids

The protective relay design for MicroGrids must be different from what has historically been used for grid distribution systems because MicroGrids add a significant number of electrical sources to a customer's system, which has historically contained only loads. Some of the differences resulting from this change are obvious; for example, once sources are added, energy can flow in either direction through protection system sensing devices. There are no two-directional flows on most radial systems. A more subtle difference between MicroGrids and traditional grids is that MicroGrids will experience a significant change in short circuit capability when they switch from grid-connected to island operation. This change in short circuit capability will have a profound impact on the vast majority of protection schemes used in today's systems, which are based on short-circuit current sensing.

The protection issues that must be resolved for MicroGrids will be discussed in two scenarios:

1. The first scenario is "normal" operation, in which the MicroGrid is connected to the bulk power provider grid when an event occurs. The protection system must determine the response of the individual DER that make up the MicroGrid, as well as the response of the device that will switch the MicroGrid to island operation. This device is labeled "Separation Device" in Figure 6.1.
2. The second scenario involves an event on the MicroGrid while the MicroGrid is in island operation mode.

6.1 Events Occurring During Normal Operation

"Normal operation" in this context means that the MicroGrid is connected to the grid (i.e., the main Separation Device, indicated in Figure 6.1, is closed.) The issues addressed in this operational scenario are the responses of the individual DER and the entire MicroGrid to events on the grid and to events within the MicroGrid.

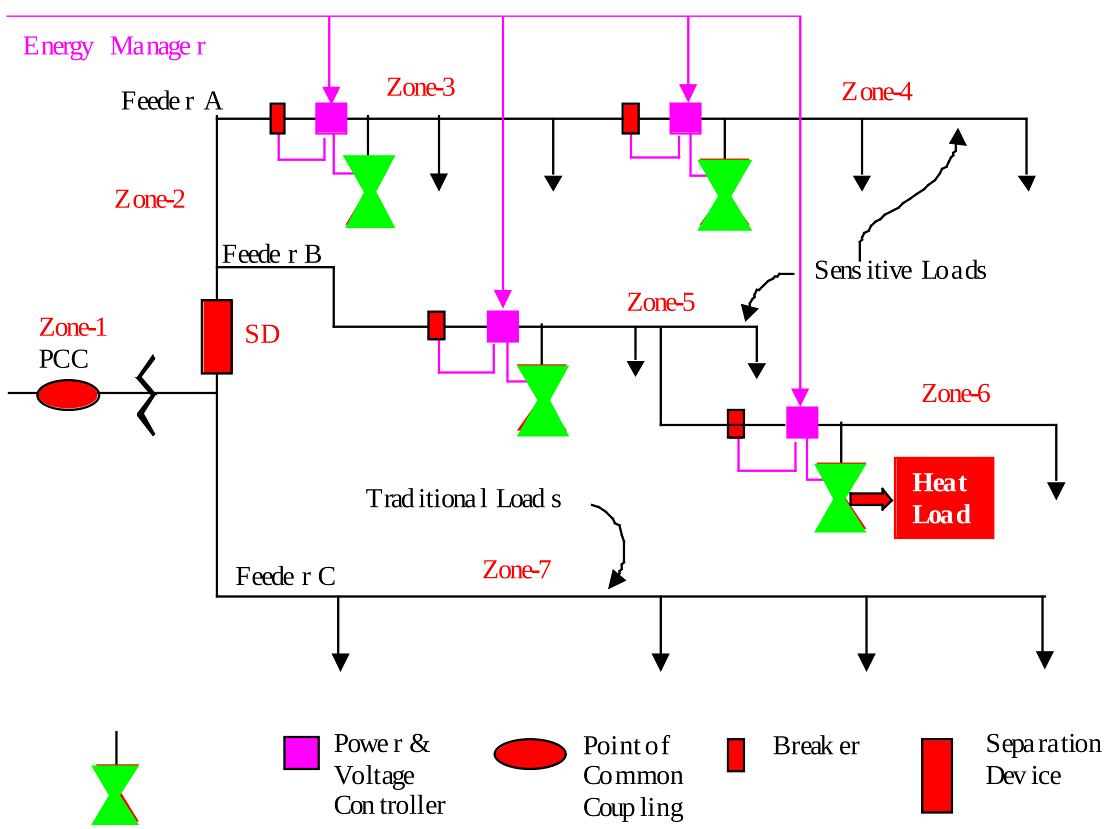


Figure 6.1 Faults on the MicroGrid

The appropriate response to an event on the grid will vary depending on the requirements of the MicroGrid loads. For example, if the MicroGrid loads are mainly retail enterprises, the main concern will be to keep the lights on so that businesses can continue serving customers. Any sensitive loads, such as computers associated with cash registers and inventory control, should have dedicated uninterruptible power supply (UPS) systems so that a brief outage (i.e., several seconds) will not affect the enterprise's capacity to continue with business as usual.

If the businesses in the MicroGrid include sensitive loads such as those that are part of many manufacturing lines, the outage times that can be tolerated may be significantly smaller than in the retail customer example above. This is particularly true if the businesses in question participate in the MicroGrid expressly because it provides reliable power supply and thus these customers have not invested in UPSs. If these businesses include semiconductor manufacturers, their equipment may meet the SEMI F47 standard, which has very tight voltage tolerance requirements. These customers will have high expectations of reliability from a MicroGrid.

Events on the Grid

Events on either side of the transformer or on Feeder C require two responses. The first is opening the Separation Device ("SD") in Figure 6.1 to island Feeders A & B from the fault. The remaining Zones-1 & 7 represent a traditional system with no distributed generation or special protection provision. As noted above, the rapidity with which isolation must be accomplished to avoid disruption to customers depends on the specific loads on the MicroGrid.

The high-speed fault interruption device that is necessary to disconnect the MicroGrid is noted in Figure 6.1 as the Separation Device. Depending on the voltage class, the speed of operation required, and fault current availability, this device may vary from a molded-case circuit breaker with shunt trip to a high-speed static switch. In all cases, a protection scheme will need to be designed for the characteristics of the specific interconnection so that the MicroGrid separation device will trip as needed. This scheme may be relatively simple, such as monitoring current magnitude and direction on each phase and sending a trip signal to the separation device if preset limits are exceeded, or it may be a relatively complex scheme that monitors waveform and attempts to achieve the much-discussed quarter-cycle trip time.

The individual DER in the above scenario must have protection schemes that enable them to continue to operate while the sensing and switching takes place disconnecting the MicroGrid from the grid. That is, the event should not trip the DER until the protection scheme has had a chance to separate the MicroGrid from the bulk power producer. If the fault remains on the MicroGrid after disconnection, and the event is determined not to be on the grid, a second set of protective decisions must be made, which will be discussed below.

Nuisance (avoidable) separations must also be considered. They will not usually result in loss of load to MicroGrid customers, but they can result in increased costs because of increased operation of the MicroGrid separation device, which will reduce its lifetime and increase labor to restore normal operations. The current draft of IEEE standard P1574 requires separation for certain voltage and frequency perturbations. These requirements are being carefully scrutinized to ensure that adequate protection is provided and nuisance trips are minimized.

Events on the MicroGrid While Connected to the Grid

From the perspective of the individual DER and individual MicroGrid loads, there is no way to distinguish between an event that occurs on the feeder supplying the MicroGrid that is on the grid side of the MicroGrid disconnecting device and an event that is on the MicroGrid side of this device, as indicated by Zone-2 on Figure 6.1. However, the responses to these two events should be different. As discussed above, the response to the event on the grid side of this device should be to separate the MicroGrid from the grid and maintain normal MicroGrid operation. Note that "maintain normal operation" means keeping loads functional; to accomplish this, the DER control method may need to be altered from the method used while the MicroGrid is grid connected in order to account for the significantly "softer" MicroGrid operation in the absence of grid support. This altered control is discussed in section 5.0.

The response to an event on the MicroGrid side of the separation device will include opening the separation device in addition to taking appropriate isolation measures within the MicroGrid. For example, a Zone-2 fault in Figure 6.1 would require opening of the MicroGrid Separation Device as well as opening the two circuit breakers connecting Feeders A & B to the main bus.

In the case of a fault within the MicroGrid, separation from the grid should be timed to coordinate with the protection "upstream" (in the direction of the grid source) from the main MicroGrid Separation Device. This coordination will depend on the protection philosophy of the interconnecting grid. Typical coordination might require that the MicroGrid Separation Device trip before any upstream device trips, to minimize the number of customers affected by a particular event. Note that the time required to open the separation device in this case may be different than the time required to open the same device in response to an event on the grid side.

In addition to the opening of the MicroGrid Separation Device, it will be necessary to isolate from the rest of the MicroGrid the line segment within the MicroGrid that contains the event, as discussed above for a Zone-2 fault. How this is accomplished will depend on the features and complexity of the MicroGrid. The basic responses of protective devices within the MicroGrid will be the same as those discussed below for the isolated MicroGrid.

Resynchronization

Finally, once service has been restored to the grid the MicroGrid must have the means to synchronize and reconnect with the grid. Ideally, this should take place as soon as the grid has had an opportunity to pick up all previously disconnected loads and to stabilize, which may require several seconds to several minutes, depending on the nature of the feeder and loads. The MicroGrid must have a control scheme that can bring all DER on the MicroGrid into synchronization with the main bulk power provider, based on measuring the voltage on both sides of the separation device. Whether this resynchronization and reconnection are done automatically or manually may vary depending on the characteristics of the MicroGrid and the interconnecting grid. Resynchronization philosophies and techniques must be studied to determine appropriate approaches.

6.2 Events on the Isolated MicroGrid

Consider, as discussed in the preceding section, an event that occurs on the MicroGrid side of the Separation Device. The two Feeders A & B have protection to allow isolation of the minimum number of generators using the line breakers. For example, a Zone-4 fault should activate the nearest breaker isolating the fault with minimum disturbance to the rest of the loads. For a fault in Zone-3 all loads on Feeder A would be isolated and shutdown. Faults in Zone-5 would isolate Feeder B

The response of these protective devices within the MicroGrid will vary dramatically depending on the complexity of the MicroGrid. An isolated MicroGrid that contains only one source may be able to employ a protection scheme similar to that used on a conventional radial distribution system. More complex MicroGrids with a number of DER will require more complex protection schemes. Decisions about the cost and complexity of protection schemes will depend on the needs of the MicroGrid.

For a MicroGrid in which customers each have adequate DER to serve their own energy needs, protection can be simple: customers can each isolate themselves from the remainder of the MicroGrid in response to an event. However, this protection scenario fails to take advantage of the diversity of load and generation that is possible in a MicroGrid. An approach that more effectively shares the resources of a MicroGrid will necessarily require more complex protection. Zone-3 fault in Figure 6.1, for example, will require that the circuit breaker for Feeder A to trip. As a result, the loads in Zone-3 will not be served (this is unavoidable without individual load UPSs) while those in Zone-4 can remain active. However, the method for detecting Zone-3 is not as straightforward as it might seem because of the dramatically reduced short-circuit current available on the isolated MicroGrid, as will be discussed in the next subsection.

Reduced Short-Circuit Current Availability

When a fault occurs on the isolated MicroGrid, the MicroGrid's reduced short-circuit current capability has a significant impact. When the MicroGrid is connected the grid sources could provide fault current that is orders of magnitude greater than load current. This high fault current is easily distinguished from load current and thus is conventionally used to detect faults on radial distribution systems.

Most conventional distribution protection is based on short-circuit current sensing. There is a large class of DER – including fuel cells, many microturbines, photovoltaic systems, many wind systems, and battery energy storage systems – that use inverters to interface with the grid. This class of DER may be capable of supplying only twice the load current or less to a fault, so the orders-of-magnitude larger fault current on which conventional overcurrent protection is based is not present. Some overcurrent sensing devices will not even respond to this small amount of overcurrent; those that do respond will take many seconds to do so rather than the fraction of a second that is required. Thus, alternate means of detecting an event must be adopted. There are alternate means available, such as the use of impedance methods, zero sequence current and/or voltage relaying and differential current and/or voltage relaying. The application of these techniques to distribution and customer systems is not well understood and need serious attention.

7. MicroGrid Economics

This section addresses some of the economic issues related to MicroGrids. Since the paper takes a medium term view, looking to a paradigm of DER deployment that is a few years to a decade in the future, it attempts to describe some of the more fundamental economic questions that must be addressed. Significant issues at the center of the current policy fray are deliberately skirted. This stance is not intended to suggest that many of the questions at the fore of the current policy debate, e.g. standby charges, net metering, public utility status of the MicroGrid etc., are unimportant. On the contrary, some of the regulatory issues surrounding limits on the ability of small generators to serve loads of neighboring customers clearly crucial, and of course they will have a significant bearing on the viability of DER. However, knowing that the outcome of these debates cannot be foreseen at this time and that the regulatory and business structure of the industry could change significantly over the coming years, it seems inappropriate to focus on them first. The approach taken here is conservative in the sense that it is implicitly assumed that the MicroGrid will have to be viable without the establishment of efficient markets for the various service streams that it may provide, and yet cavalier in that many obvious regulatory barriers are not addressed.

It has to be argued that increasing small-scale generation close to loads may be key to expanding power supply because the current centralized power system may not be sustainable. Over the coming decades, construction of new large centralized power generating plants and their associated transmission lines is unlikely to keep pace with the seemingly inexorably growing electricity appetite of the developed world. Environmental concerns, dwindling available sites, and a general NIMBY or BANANA suspicion of power facilities will make the current centralized generating paradigm incapable of adequate expansion.[3] Furthermore, based on experience to date, it appears that emerging restructured electricity markets will deliver volatile commodity electricity prices and an erratic investment program that results in unpredictable electricity supply reliability. In short, MicroGrids will not be competing with the centralized power system of today but with the erratic growth of that system in an environment hostile to its expansion. At the same time, customer demand for highly reliable power for vital sensitive equipment is growing and the potential of CHP is one of the few available options for significantly improving overall energy conversion efficiency.

The economics or business case for the MicroGrid determines the configuration and operation of the MicroGrid. Issues of MicroGrid economics can be roughly divided into three categories:

1. The first concerns the basic economics of optimal investment and operation of technologies available to the MicroGrid. These are problems that, at least at the distribution system scale, have received intense academic scrutiny; as a result, established and reliable tools are available to guide operations and should, with some adaptation to the specifics of MicroGrids, be effective. In other words, much of our accumulated knowledge about the operation of grid scale systems can be applied to MicroGrids.
2. The second concerns some of the unique aspects of MicroGrids that will require innovation. In general, these are areas in which MicroGrids differ significantly from distribution systems,

[3] NIMBY = not in my backyard, BANANA = build absolutely nothing anywhere near anybody.

for example, the possibility of providing heterogeneous levels of reliability to various end uses, and the critical central importance of some operational constraints, such as noise, that are relatively insignificant to bulk power provider's economics.

3. The third concerns the relationship of the MicroGrid to the distribution system. In many ways these problems resemble familiar ones related to the interface between customers and utilities, for example, the need to provide a real-time price signal to the MicroGrid so that optimal use of resources by both the MicroGrid and grid can be achieved simultaneously. Other problems are more novel and challenging. For example, MicroGrids' ability to participate in grid-scale ancillary services markets will most likely be limited by voltage and losses, but MicroGrids could still provide some local services, such as voltage support. Creating a market for localized voltage support, or even placing meaningful value on it, seems unlikely at the present time.

7.1 MicroGrids and Traditional Power System Economics

A MicroGrid is designed, installed, and operated by a customer or group of customers primarily for their economic benefit. Although MicroGrid participants may be concerned about the environmental effects of their energy supply system as well as about noise and other similar considerations, the most important benefit that participants seek is a lower total energy bill (i.e., combined bill for heat, electricity, and transportation). The MicroGrid may be able to operate some or all of its end uses at lower cost than would be possible on the grid. The cost of delivered energy from the traditional power system includes losses, customer services, congestion, and other costs that together typically exceed the generation (bus bar) cost alone. The MicroGrid will likely have smaller losses as well as other advantages that will lower its costs relative to the costs of the distribution system.

Table 1 shows some present-day cost information for some small-scale generating technologies currently available for deployment in MicroGrids. The first notable feature of Table 1 costs is that on-site generation is currently competitive with central station generation at certain times and in certain places. However, the currently available technology that is apparently cheapest, reciprocating engines, has some pronounced disadvantages, notably air quality impacts (and the associated difficulty of getting related permits), noise, and interconnection costs. During the coming decade, costs of other, new technologies are likely to fall significantly, so that other options, fuel cells for example, may be the cheapest on-site generating technology available under some circumstances. Fuel cells and other types of DER have fewer disadvantages than reciprocating engines. Even without consideration of other benefits of DER, their economics suggest that they will challenge the economies of scale that originally motivated reliance on traditional central station generation. On the other hand, the current system offers low risk and transaction cost to the customer. Without considering for the moment how MicroGrids might be financed and developed, there is no doubt that going the MicroGrid route will incur significant costs that are not seen in the Table 1 representation of equipment costs. While many of these are self-evident, such as the danger of installation cost overruns, some are subtler. For example, it should be noted that for the MicroGrid to operate in island mode as a low inertia system, sources of storage as described in section 5.1 will be required. The total requirement for this equipment is unclear at present, but the costs involved could be significant and this consideration must be brought into the economic evaluation. This additional cost must be traded off against the added benefits of islanding capability from the customer perspective, and against the cost of maintaining high system reliability from the grid perspective.

Table 1: Cost Information of Select Generation Technologies

	Name	DER Type	Source	Nameplate kW	lifetime (a)	$/kW cost FOB cost	$/kW cost Turnkey cost	OMFix $/kW/a	OMVar $/kWh	Lev Cost c/kWh	Heat Rate kJ/kWh
1	MTL-C-30	MT	SCE	30	12.5	1200	1333	119	in Fix O&M	12.14	12,186
2	PAFC-O-200	PAFC	TAG	200	12.5	3500	**PR**	**PR**	**PR**	13.68	**PR**
3	DE-K-30	Diesel Backup	manufacturer	30	12.5	473	1290	26.5	0.000033	5.51	11,887
4	DE-K-60	Diesel Backup	manufacturer	60	12.5	290	864	26.5	0.000033	6.30	11,201
5	DE-K-500	Diesel Backup	manufacturer	500	12.5	166	386	26.5	0.000033	4.65	10,314
6	DE-C-7	Diesel Backup	manufacturer	7.5	12.5	213	627	26.5	0.000033	N/A	10,458
7	DE-C-200	Diesel Backup	manufacturer	200	12.5	135	416	26.5	0.000033	4.94	9,944
8	GA-K-55	Gas Backup	manufacturer	55	12.5	290	970	26.5	0.000033	7.55	12,997
9	GA-K-500	Gas Backup	manufacturer	500	12.5	408	936	26.5	0.000033	7.33	12,003
10	WD-10	Wind	Bergey Windpower	10	12.5	2805	6055	5.7	0	27.05	
11	PV-5	PV	Jeff Oldman, Real Goods	5	20	7150	8650	14.3	0	55.23	
12	PV-50	PV	Jeff Oldman, Real Goods	50	20	5175	6675	5	0	42.62	
13	PV-100	PV	Jeff Oldman, Real Goods	100	20	5175	6675	2.85	0	42.62	

*PR = Data considered proprietary

Straightforward application of engineering-economic principles can help determine which technologies are likely to be attractive to MicroGrids and how these technologies will be deployed and operated. In many regards, the economics of MicroGrids are similar to those of grid-scale systems. For example, the rules of economic dispatch apply to both, and minimizing costs for both types of systems requires that the lowest-possible-cost combination of resources must be operating at all times, to the extent that equipment characteristics allow. Purchase and sale of electricity is possible in both grid-scale and MicroGrid systems, and both of these activities may occur at different times. The variety of duty cycles required implies that the optimal combination of resources chosen by the MicroGrid will be technologically diverse, like the combinations used in utilities. In this context, technologically diverse resources include those used to meet a range of demands: baseload duty-cycle needs, peak demand, and others degrees of demand between these two extremes. Different types of generators will be most efficient at meeting different types of demand. The classic solution in grid systems is that high-capital, low-variable-cost technologies are suitable for the baseload, and generators with the opposite qualities are suitable for peak demand; this principle could prove equally true for MicroGrids.

Although there are numerous similarities between MicroGrid and grid economics, some aspects of traditional MicroGrid economics are novel and will require rethinking or extending familiar tools. Two notable examples are joint optimization of heat and power supply and joint optimization of loads and supply.

CHP is a relatively underdeveloped area of power system economics. Use of CHP is common in U.S. industry, and about nine percent of U.S. electricity is currently generated in CHP systems. A major non-industrial application is district-heating systems, which are extensively used in some northern European cities, such as Warsaw. However, these systems have tended to develop in response to isolated opportunities for use of waste heat; until recently, use of heat was not one of the central objectives of grid-scale power system development. A key reason for current rethinking of this issue is the drive to reduce carbon emissions. Increasing the overall efficiency of power generation in the U.S. from the expected approximately 33 percent in 2010 to approximately 70 percent could, without fuel switching, provide one half of the approximately 500 Mt overall reduction in total U.S. carbon emissions suggested by the Kyoto Protocol for that year. CHP is the only approach that could deliver power generation efficiency improvements of this magnitude.

As a consequence of the scant historic interest in CHP, grids have placed generation stations close to convenient cooling resources rather than at locations that would facilitate use of waste heat. Because one of the driving forces for MicroGrids is the desire to move power generation toward using waste heat, CHP will likely be at the heart of MicroGrid economics.

There are three immediately apparent potential applications of CHP in MicroGrids:

1. space heating, domestic hot water heating, and sterilization;
2. industrial or manufacturing processes; and
3. space cooling and refrigeration through use of absorption chilling.

To show that the attraction of exploiting CHP opportunities will be a key motivator for customers to self-generate electricity, it is sufficient to show technically feasible examples in which CHP applications of any of the three types can lower the joint cost of providing electricity and heat/cooling relative to the cost of providing these services from separate purchased sources (typically purchased power and natural gas come from the grid). To show that CHP alone is a strong motivator for multiple customers to join together and form MicroGrids, it is also necessary to show that aggregation of heat and power loads has economic benefits. It is not difficult to see that this would be true in certain cases, e.g. a bottling plant with modest space heat and large sterilization loads might optimally produce more electricity that it can by itself consume and would benefit by being part of a MicroGrid. However, a full economic case has not yet been made regarding the degree to which CHP opportunities will motivate customers to form MicroGrids.

Joint optimization of demand and supply is a second, key area where some extension of traditional power system economics is required for MicroGrids. In grid-scale systems, control of loads is usually addressed during analysis and planning as demand-side management (DSM), load control, or load shedding and interruptible tariffs or contracts. MicroGrids are different in a number of key respects. First and most importantly, the marginal cost of self-generation at any point in time is well known to and actually paid by the MicroGrid. In other words, for power generated by the MicroGrid, the vagaries of investment cost recovery, cross subsidies, and inaccurate metering and tariffs are all avoided. This is not to say that costs outside the MicroGrid will be well represented in tariffs, environmental rules, etc. The record to date on tariff reform to improve cost signals to customers is pitiful and emergence of the MicroGrid will not change this balance. But within the MicroGrid, the generator and consumer are one and the same decision maker, and the struggle to coordinate investment and operating decisions on what were formally thought of as opposite sides of the meter is eliminated. The MicroGrid can readily know both its marginal cost of providing power at any point in time and the equivalent costs of investments in energy efficiency, and can, with some introspection and analysis, decide what its cost of curtailment is and then can readily trade off the three. This simple reality elevates load control to a new level of importance in MicroGrids and requires an extension of current thinking.

7.2 Newer Economic Issues in MicroGrids

The second group of economic issues related to MicroGrids covers some unique MicroGrid features that require innovation in traditional power system economics. In general, these are areas in which MicroGrids differ significantly from grid systems, for example, the possibility of providing heterogeneous levels of reliability to various end uses within the MicroGrid, and the central importance of some operational constraints, such as noise, that are relatively insignificant to grid economics.

Power systems have traditionally been designed and operated around the concept of "universal service," which holds that the quality and reliability of power delivered to all customers must meet roughly the same standard. In practice, there are significant deviations from this universal standard, in part because of the problems of serving vast and diverse geographic areas, but the goal is still to adhere to a universal standard. A key motivation of MicroGrids is the desire to move control of power reliability and quality closer to the point of end use so that these properties can be optimized for the specific loads served. Simple economics tells us that tailoring power reliability and quality to the end uses served can deliver benefits simply because, in times of energy shortfall, energy can be moved from lower value end uses to higher value ones. Also, given that providing higher quality and reliability can be assumed to entail some cost, savings will result if higher quality power is not provided to end uses for which it is not required. Traditional power system economics has paid considerable attention to some aspects of valuing power quality and reliability, notably to estimating the cost of general outages and to schemes of priority pricing that would allow customers to exercise choice in their level of reliability; however, the notion that systems could be built around heterogeneous service quality is a quite new. Another related issue (addressed in more detail below) concerns the optimal level of quality for the universal service provided by the grid. If widespread MicroGrids effectively serve sensitive loads with locally controlled generation, back-up, and storage, the bulk power system benefits because it is no longer constrained to set its reliability requirements to meet the needs of sensitive local end uses.

7.3 Economic Issues Between MicroGrids and Bulk Power Systems

The third set of economic questions related to MicroGrids covers the relationship of MicroGrids to the grid. A fundamental tenet of the MicroGrid paradigm is that the MicroGrid must represent itself to the grid as a good citizen; that is, it must adhere strictly to the rules that apply to all connected devices. The MicroGrid must behave as a legitimate customer or generator or both, and may enhance those traditional economic roles.

Delivering true price signals in time and space raises some significant problems. Because MicroGrids embed new generation within the existing radial distribution system, system upgrades that would otherwise be necessary to meet growing load can be postponed or entirely avoided. Ideally a price signal could be delivered to customers within the distribution system at times of increasing congestion in a form that would encourage MicroGrid development and investment in generation and/or load control to mitigate the congestion. However, this is difficult in practice. The design of distribution systems in densely populated areas is quite flexible so that any one end-use load could be served by several alternative system configurations. Thus, the congestion costs seen by any one MicroGrid would depend on a somewhat arbitrary configuration of the network that could change abruptly, thus disrupting the economics dependent on that configuration.

MicroGrid participation in markets is both possible and desirable, but there are some likely limits to it. The low voltages of the MicroGrid will inhibit its ability to efficiently deliver energy beyond the substation, and provision of ancillary services will be similarly limited. One service that the MicroGrid can readily provide, however, is interruptible load, taking advantage of its on-site generation and control schemes to protect sensitive loads. This could be a valuable contribution to the overall health of the power system as market responses to load changes become less and less feasible when response times must be within seconds or minutes.

8. Conclusion

The Consortium for Electric Reliability Technology Solutions is pioneering the concept of MicroGrids as an alternative approach to integrating small scale distributed energy resources into electricity distribution networks, and more generally, into the current wider power system. Traditional approaches focus on minimizing the consequences for safety and grid performance of a relatively small number of individually interconnected microgenerators, implying, for example, that safety requires they instantaneously disconnect in the event of system outage. By contrast, MicroGrids would be designed to operate independently, usually operating connected to the grid but islanding from it, as cost effective or necessary to maintain performance.

A MicroGrid is a semiautonomous grouping of generating sources and enduse sinks that are placed and operated for the benefit of its member customer(s). The supply sources may be driven by a diverse set of prime movers and/or storage devices. The key distinguishing feature of the MicroGrid is that sources are interconnected by Microsource Controllers. These power electronic devices maintain energy balance and power quality through passive plug and play power electronic inverter features that allow operation without tight central active control or fast (on time scales less than minutes) communication. They also permit connection and disconnection of devices without need for any reconfiguration of equipment, preexisting or new. Overall economic operation within constraints such as air quality permit restrictions, noise limits, etc., as well as maintenance of a legitimate façade to the grid is achieved entirely through slow (on time scales of minutes or longer) communications with a central Energy Manager.

A critical feature of the MicroGrid is its presentation to the surrounding distribution system as a single controlled system, akin to a current customer, or possibly a small generation source. Key to this characteristic is reliance on the flexibility of advanced power electronics that control the interface between microsources and their surrounding AC system. The MicroGrid architecture ensures that its electrical impact on the distribution grid at least ensures it to be a good citizen, that is one that does no harm. In some circumstances, it may qualify as a model citizen, that is one that adds benefits to the grid such as reducing congestion, offsetting the need for new generation, supplying local voltage support, enhancing stability, or responding to rapid changes in load levels.

LBNL-50829

Consortium for Electric Reliability Technology Solutions

White Paper on

Integration of Distributed Energy Resources

The MicroGrid Concept

Appendices

Prepared for

Transmission Reliability Program
Office of Power Technologies
Assistant Secretary for Energy Efficiency and Renewable Energy
U.S. Department of Energy

Energy Systems Integration Program
Public Interest Energy Research
California Energy Commission

Prepared by

Robert Lasseter, Abbas Akhil, Chris Marnay, John Stephens,
Jeff Dagle, Ross Guttromson, A. Sakis Meliopoulous, Robert Yinger, and Joe Eto

April 2002

The work described in this report was coordinated by the Consortium for Electric Reliability Technology Solutions, and funded by the Assistant Secretary of Energy Efficiency and Renewable Energy, Office of Power Technologies of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and by the California Energy Commission, Public Interest Energy Research Program, under Work for Others Contract No. BG 99-39.

APPENDIX A. MicroGrid Technologies

Many small (less than 250-kW) generation and storage technologies are already being used to shave peak generation and provide back-up generation during power system outages. This appendix gives a brief overview of each of the major technologies currently in use or expected to soon become available. These technologies are divided into two major categories: generation and storage. Generation technologies described are: microturbines, fuel cells, photovoltaic cells, solar thermal arrays, wind turbines, reciprocating engines, and small hydro installations. Storage technologies addressed are: batteries, flywheels, superconducting magnetic energy storage systems, and supercapacitors. All of these distributed generation and storage technologies could be grouped together into MicroGrids.

A. 1 Small (<250-kW) Distributed Generation Technologies

The technologies discussed below all use a fuel or power resource that is converted to standard North American 60-Hz electrical power. For most microturbines, fuel cells, and photovoltaic cells, electrical power is generated as direct current (DC) voltage and converted to alternating current (AC) using an inverter. In other words, unlike in large-scale power systems, an power electronic inverter isolates the small mechanical, chemical, or solid-state generator from the power grid. For solar thermal, wind, reciprocating engine, and small hydro generators, turbine shaft rotation is converted directly to AC power. The difference in conversion for technologies that require an inverter and those that produce AC power directly is important for the design and operation of a MicroGrid made up of distributed generation resources.

Microturbines

Microturbines are composed of a generator and small gas turbine mounted on a single shaft. The turbine technology is based on a refinement of automotive turbo chargers and military engines. Microturbines rotate at high speeds, some at nearly 100,000 rpm. A permanent magnet generator spinning at this high shaft speed produces the power in the form of high-frequency AC, which is converted to DC and then to standard 60-Hz AC using an inverter. Most microturbines are fueled by natural gas but can also use liquid fuels such as diesel or jet fuel. These units currently range in size from 30 to about 100 kW; larger units are under development. Most microturbines also have a recuperator to recycle some exhaust heat back to the combustor. A microturbine with recuperator typically has 20-30 percent efficiency. Utilization of waste heat can increase overall system efficiency (electricity and heat) to 70- 80 percent. Because the combustion process is closely controlled and relies on relatively clean burning fuels, microturbines typically produce few emissions.

Microturbines are just now coming to market; one major U.S. supplier is producing units for installation, and several other manufacturers are performing final testing of units that are expected to come to be available on the market in the near future. Many microturbines can operate as stand-alone resources or in parallel with the electrical grid. When operating parallel to the grid, they generally produce fixed power output or function in peak-shaving mode. In the stand-alone mode, microturbines must regulate voltage and frequency and follow load changes. Rapid load following is accomplished using an on-board battery or fast-response fuel control.

Because microturbines do not produce significant emissions, they are expected to be widely applicable in areas with strict pollution controls. With the use of combined heat and power (CHP), microturbines could generate on-site power at costs competitive with those for current purchased power. The limitations of microturbines are noise and emissions. Although these impacts are relatively small, microturbines are located near the point of energy use, so they will likely have greater effect on local residents than the noise and emissions produced by modern central power stations, which are usually located far from population centers.

Fuel Cells

A number of fuel cell technologies are either under development or currently being used to generate power. The attraction of fuel cells is their potential for highly efficient conversion to electrical power (35 to 55 percent without heat recovery). The only technology in general use today is the phosphoric acid fuel cell, which is available in the 200-kW size range. This fuel cell operates at about 40 percent conversion efficiency. Because this device operates at 400 degrees F, waste heat is available as steam, which boosts the overall fuel conversion efficiency. A number of other fuel cell technologies are being developed. For the power industry, these include: proton exchange membrane (low-temperature, hydrogen fueled), molten carbonate (high- temperature), and solid oxide (high-temperature).

All fuel cell technologies operate in a similar manner electrically although they differ in operating temperature, charge carrier (H^+, O^{-2}, CO_3^{-2}, or OH^-), electrode, electrolyte, catalyst, and current collector/flow field materials. Introduction of a fuel (generally hydrogen) to the fuel cell stack where catalyst material is impregnated in the electrodes and an ion-conducting electrolyte is present causes the separation of ions and electrons and results in electron movement. This movement generates a DC voltage on the stack terminals that is proportional to the number of cells in the stack. The DC voltage is sent to an inverter where it is converted to 60-Hz power. The fuel cell appears to the electricity grid as an inverter, similar to a microturbine.

The ability of a fuel cell to change load levels is dictated by its ability to produce more voltage through consumption of additional fuel. Because most fuel cell stacks are designed to use hydrogen, fuels that are readily obtainable (e.g. natural gas, gasoline, diesel fuel) need to be "reformed" into free hydrogen for use by the fuel cell stack. Reforming can take place outside the fuel cell (for low-temperature technologies) or inside the fuel cell (for high-temperature technologies). The emissions of the fuel cell stack itself are generally limited to water vapor, exhaust air that is depleted of oxygen, and, for direct- -hydrocarbon and direct-carbon fuel cell systems, carbon dioxide. Reforming processes add low levels of nitrogen oxides, carbon monoxide, and hydrocarbons, depending on the specific technology and fuel used.

Although most fuel cell technologies are not yet commercial, they show great promise for use in MicroGrids because they combine high efficiency, high reliability, and quiet operation. Their biggest drawback is high cost.

Photovoltaic Cells

Photovoltaic (PV) devices have been in existence for many years since their early use in the U.S. space program. They rely on sunlight to produce DC voltage at cell terminals. The amounts of voltage and current that PV cells can produce depend on the intensity of sunlight and the design of the cell. PV systems use cell arrays that are either fixed or track the sun to capture additional energy. Because solar energy is a diffuse resource, it takes a large area of PV cells to produce significant power. At a typical cell conversion efficiency of 10 percent, about 10 m^2 of panels are needed to provide a peak power of 1 kW. To reduce the number of costly PV devices used, mirrors or lenses can be used to concentrate sunlight on to the cells. This increases the PV cell output but requires tracking devices to insure that the array is aligned with the sun.

Photovoltaics, like microturbines and fuel cells, generate DC voltage that must pass through an inverter to produce 60-Hz alternating current for distribution on the utility grid. A PV system's capability to track load changes is limited by available sunlight. Storage is required for stand-alone systems if power requirements exceed available sunlight.

While the sun shines, PV systems operate highly reliably, quietly, and with no emissions. Their largest drawbacks are their high initial cost, the intermittent nature of the solar resource, and the large collection areas they require.

Solar Thermal

Although there are a number of large-scale (several-megawatt) generation technologies in the solar thermal field, the main technology for small-scale generation is the sterling dish. This technology is being tested in the 10- to 25-kW range. In this system, light is concentrated on a small receiver by a sun-tracking array of mirrors. The heat collected by the receiver is transferred to the hot end of a sterling engine. The sterling engine uses working fluid in a closed cycle to push pistons and generate shaft rotation. In a sterling dish, shaft rotation is used to spin an induction generator that is connected to the electric grid.

Like PV systems, sterling dishes have a power output that is fixed by the amount of solar input. In a closed system, storage is required to handle power requirements in excess of the solar energy available at any given time. Because sterling dishes use induction generators, these systems are not easily adaptable to stand-alone operation in a MicroGrid. In the near term, the cost of this technology will remain high.

Wind

Wind generation has been commercially available for many years. The main push has been in large wind farms where wind turbines from 700 kW to 1.5 MW are available and in use. Several smaller wind turbines (<250 kW) are available for use in MicroGrids. These machines typically use an induction generator driven by a rotor with blades. As is true for the solar options, the wind generators' power output is determined by the availability of their energy source. When the turbine is operating in stand-alone mode, any power requirement in excess of the wind energy available must be supplied by storage systems or other generation. Because they commonly use induction generators, small wind systems are not easily adapted to MicroGrid operation unless other sources supply voltage and frequency control.

Small Reciprocating Engines

Reciprocating engines that run on various fuels are available in small sizes and up to several megawatts. Currently available engines are typically intended for stand-alone or back-up use. These engines, especially the larger ones, have good efficiencies (30 to 40 percent). They operate in stand-alone applications like scaled-down generation plants with synchronous generators capable of controlling voltage and frequency. Waste heat from these units can help boost overall system efficiencies.

Reciprocating engine generators are a mature, low-cost, familiar technology with some attractive benefits for MicroGrids. Their main disadvantages are noise, maintenance costs, and emissions. Emissions depend heavily on the fuel used. Clean-burning fuels, such as natural gas, could result in acceptable emissions profiles, especially if control technologies were used. However, the most common fuel currently in use by far is diesel, which causes serious emissions problems and would preclude the regular use of this technology.

A. 2 Storage Technologies

Storage is important in the MicroGrid both because peak loads are expensive to serve with purchased power and because MicroGrid generation sources may not be able to respond to load changes as needed. Load changes are usually caused by short-lived events, such as fast transients resulting from starting of motors or turning on/off of equipment, or from slower changes that exceed the ramping capability of generation available at any given time.

All the storage systems mentioned in the sections below require power electronics to convert the stored power to standard, 60-Hz, AC, utility-grade power. These systems can be designed to switch into operation in subcycle time frames, so they are ideal for tracking fast load changes or immediately providing back-up if utility power is lost.

Batteries

Batteries are the traditional method of storing electrical energy; there is considerable operational experience with battery systems. Lead-acid batteries, available in almost any size, are used in many applications that require back-up power. Batteries using other chemistries are now also available commercially. Recent improvements have increased energy storage density and extended battery lifetimes. Discharge rates are determined by the battery's design and the chemical reactions used for energy storage.

Batteries store energy in chemical form and are charged/discharged with DC current. This DC current is converted to standard, 60-Hz, AC electrical power by means of power electronics. Most commercial uninterruptible power supplies rely on batteries.

Flywheels

Many improvements have been made to flywheel systems in recent years. These systems now incorporate composite rotors, magnetic bearings, and advanced power electronics. Flywheels store energy in high-speed (up to 100,000-rpm) rotating wheel-like rotors or disks connected to motor/generators. High-speed rotation is important because the amount of power stored in the flywheel is proportional to the square of the rotational speed. The flywheel is "charged" by taking utility power and converting it to drive the flywheel motor, which increases flywheel speed. During a "discharge," power is drawn from the flywheel by the generator, which slows the rotor speed. Because the output of the flywheel generator is variable, an inverter is used to convert power to standard, 60-Hz AC power.

Flywheel systems come in a wide range of sizes with differing discharge rates for different amounts of time. The flywheel stores a fixed amount of energy (kWh). It can be discharged at high power (kW) for a short time or at a slower rate for a longer period. Flywheels contain no hazardous materials and are not affected by temperature extremes as batteries are, but flywheels are costly and cannot store energy indefinitely.

Superconducting Magnetic Energy Storage

Superconductors allow the passage of electrical current without losses. Electrical energy is stored as a circulating current in a superconducting coil of wire. This circulating current establishes a magnetic field in which the energy is stored. The major energy loss in this system results from the need to cool the coil to very low temperatures. Power electronic interfaces charge and discharge the superconducting coil. Most commercial systems are somewhat larger than 250 kW in capacity. Superconductor storage technology could be adapted to larger MicroGrid applications.

Supercapacitors

Supercapacitors are very-high-capacity electrolytic devices that store energy in the form of electrostatic charge. They are composed of two electrodes with a very thin separator. Energy storage capacity increases as the surface area of the electrodes increases. Energy is stored as a DC field in the supercapacitor, and the system uses power electronics to both charge and discharge the capacitors. Supercapacitors can have very high discharge rates and could handle fast load changes in a MicroGrid.

A.3 Inverter Interfaces

There are two basic classes of microsources: DC sources, such as fuel cells, PV cells, and battery storage; and variable high-frequency AC sources such as a microturbines, whose output is converted to DC. In both cases, the DC voltage that is generated needs to be interfaced to the AC network and its loads. Power electronics provide this interface as a converter periodically switches the DC voltage polarity on the AC side to create an AC waveform of desired magnitude and phase.

A basic understanding of power electronics requires understanding of the creation of waveforms of different magnitudes, phases. and frequencies using circuits containing rapidly acting switches and energy storage elements. Power electronic devices are designed to operate like switches, but, because these devices are made of semiconducting materials like silicon, they can function much more rapidly than mechanical switches. Energy storage elements, such as inductors and capacitors, filter the sharp-edged waveforms created by the switching.

Voltage-Sourced Inverters

A circuit and switching sequence is needed that can convert the DC voltage from a microsource to three-phase AC voltage. Consider the circuit in Figure A3.1(a). On the left is a DC voltage that is provided by the microsource and connected to a three-phase AC system using double-pole switches. In reality, these switches are power electronic devices with bi-directional current flow capability and rapid switching speeds. In the current positions (1,6,2), the three-phase line-to-line voltage is: $V_{AB} = V_{DC}$, $V_{BC} = 0$ and $V_{CA} = -V_{DC}$. This strategy allows the converter to synthesize three AC square waves of voltage at the correct phase to each other. Figure A3.1 (b) shows the V_{AB} synthesized square wave. The positive voltage is achieved by the switch positions shown (1,6); negative voltage requires the opposite (3,4) position.

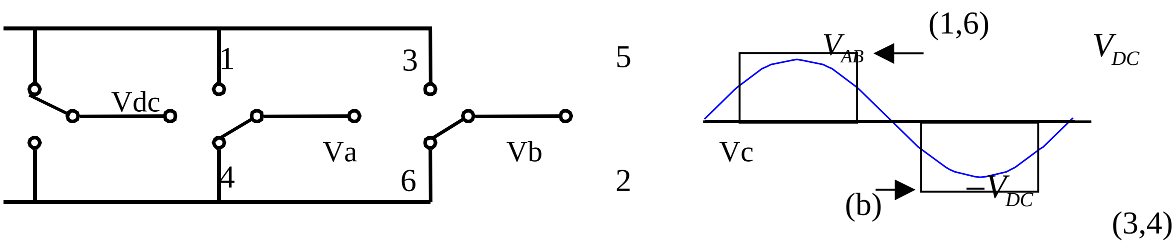


Figure A3. 1 Voltage Synthesis (a) Circuit, (b)Line-to Line Voltage

Although a square wave allows full control of rms voltage output and phase, it would require a great deal of filtering to provide the loads with the required sinusoidal waveforms. Power electronic switching devices have the ability to switch much more rapidly than the fundamental frequency, which means that *pulse width modulation* (pwm) is an option. For example, for the positive voltage section, Figure (b), the inverter can rapidly switch from the (1,6) position to the (1,3) or (4,6) position, which provides zero voltage between phases A & B. The same can be done on the negative side. This allows the instantaneous average output to be held closer to the desired fundamental output. A converter incorporating pulse width modulation requires considerably less filtering to achieve the required power quality.

In general, pulse width modulation is limited by the switching frequency of the power electronic device and the techniques of the controller. Typical switching frequencies are at least 30 times faster than the fundamental frequency. During each switching period, the inverter control selects the times of conduction or duty cycles that create the desired voltage for that period. The resulting voltage is made of pulses of different widths (hence the name pulse width modulation). The pattern and number of pulses are designed to provide the required voltage magnitude, and the pulses are placed to minimize the harmonic content. Such a pattern is shown in Figure A.3.2 for all three phases. The arrows indicate the switch position shown in Figure A.3.1 (a).

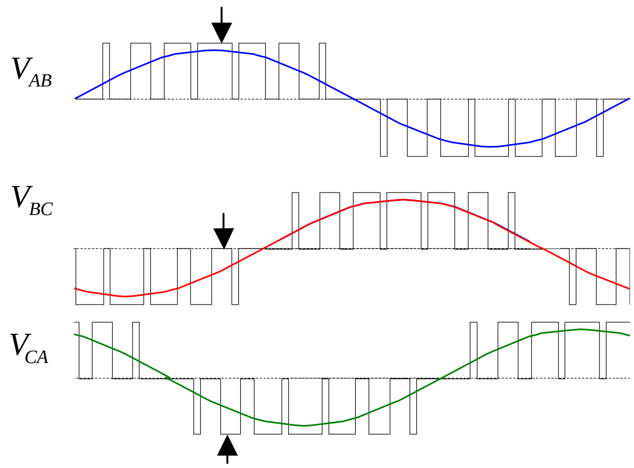
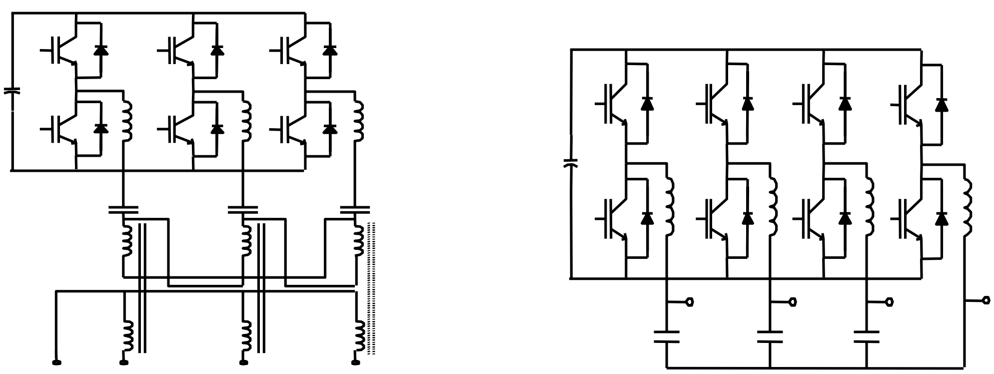


Figure A.3. 2. Three-Phase Pulse Width Modulated Voltage

Inverter Realization for Microsources

To realize an actual voltage-sourced inverter with pwm, two key issues must be addressed: implementation of switches and connection to the customer's AC system. The switches shown in Figure A.3.1 are implemented using Insulated Gate Bipolar junction Transistor (IGBT) and diodes. The advantages of IGBTs include their simple gate drives derived from voltage control requirements and their ample voltage/current ratings up to 3,000 volts and 1,200 amperes. Their switching times are less than one microsecond. IGBTs with reverse diodes are shown in place of switches in Figure A.3.3.

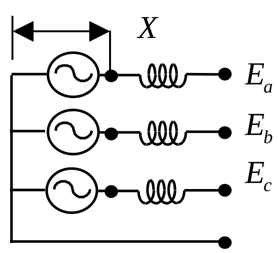


FigureA3. 3. PWM Inverters with Four- Wire Interface, (a) Using Star-Delta Transformer (b) Direct connection using four- legged Inverter

Microsources such as microturbines, fuel cells, and PV systems seldom exceed 200 kilowatts and in many cases are smaller than 100 kilowatts. This low level of power along with the need to utilize waste heat means that these sources are placed at the customer's site rather than at the utility's substation. AC systems are usually 480 volts or less with a four-wire configuration to accommodate single-phase loads. This requirement can be met using the three-legged inverter shown in Figure A.3.1 with the addition of a star-delta transformer' the center point of the star can be used to provide the extra wire [see Figure A.3.3 (a)]. Another possibility is to add a fourth leg to provide the extra connection point [see Figure A.3.3 (b)]. The operation is similar to one discussed in the section on voltage-sourced inverters above except that the DC voltage is always switched between the neutral and single- phase. This allows for direct creation of phase-to-neutral voltages rather than line-to-line voltage provided by a three-legged inverter. The differences between the two circuits in Figure A.3.3 include: the use of magnetics versus extra IGBTs and diodes, and the handling of fault current and dependents between DC and AC voltage levels. During a fault, fault current will be flowing in the four-legged inverter; in transformer-coupled systems, the fault current will circulate in the delta winding. For the transformer-coupled system the DC voltage becomes a free variable because of the turns ratio. In the direct-coupled system the DC voltage needs to be 10 to 20 percent larger than the required peak AC voltage.

Unbalanced AC Voltages

Microsources with AC voltages of 480 volts or less and a four-wire configuration to accommodate single-phase loads have unbalanced voltages because of asymmetries in the wiring and the presence of unbalanced loads. When these microsources are connected to the AC system using the inverters discussed above, there will be uneven phase currents. However, microsources may be intolerant of voltage imbalances. Field experience with ONSI fuel cells, for example, has shown that imbalances trip the current protection in the inverter because it assumes balanced currents. (This is the norm for adjustable-speed-drive protection).



$$\hat{I} = \frac{\hat{V} - \hat{E}}{X}$$

Figure A.3.4. Basic Four- Wire Source

Both inverters shown in Figure A.3.3 can be represented as shown in Figure A.3.4 to demonstrate interactions with the AC system. The voltage-sourced inverter creates three AC voltages, $V_{a,b,c}^{inverter}$ that are coupled to the AC system through three inductors, X. The current that flows in each inductor is dependent on the inverter and AC system voltages. If the AC system voltages are balanced and the inverter creates balanced voltages, the currents are equal. When the AC voltages are unbalanced, the currents also become unbalanced. The inverter has the flexibility to create unbalanced voltages between phases that can:

- Rebalance the output currents,
- Correct the system's voltage imbalance,
- Regulate the positive sequence AC voltage but not correct for the imbalance, and
- Remove the negative sequence AC voltage component that results from a voltage dip.

In general, voltage-sourced inverters have the flexibility to deal with most unbalanced situations seen in the field, but this flexibility is not currently used. The Honeywell Parallon 75 uses the system shown in Figure A.3.3(a). It can control power and reactive power flow. In situations where AC voltages are unbalanced, the currents are also unbalanced and will trip at 20 percent overcurrent in the delta winding. The Capstone 330 uses the system in Figure A.3.3(b). In island mode, the unit provides balanced three-phase system voltages. The currents are a function of the load imbalance, and the system trips when the neutral line has a power flow above one-third of the system's power rating. For highly unbalanced loads, the total output could be less than one-third the rating of the microturbine.

A4. Combined Heat and Power (CHP)

Combined heat and power (CHP) technologies, also known as cogeneration, produce electricity and heat simultaneously. This is accomplished by capturing and using the roughly two-thirds of heat that is produced and typically rejected in electricity production. As a result of this waste heat use, the overall energy efficiency of CHP systems is substantially greater than that of systems that do not have this feature.

CHP systems are more prevalent in many economies than in the U.S., where they are only commonly found in industrial facilities. For example, as of 1996, 48 percent of the domestic electricity demand in Denmark came from CHP plants. This level of CHP is believed to reduce CO_2 emissions by approximately 7-10 Mt per year, or more than 10 percent of the total CO_2 emissions of the country, compared with emissions from separate heat and power production. CHP units that are 2-4 MWe are typically the best size for Danish local district heating systems, which power approximately 100-250 households and two large institutions or a net heat demand of approximately 20 TJ. Elsewhere in Europe, the Netherlands produces about 30 percent of its power from CHP systems, Germany produces about 14 percent, and Italy produces about 12 percent. By comparison, the U.S. produces only about 9 percent of power from CHP systems. On a scale more relevant to MicroGrids, more than 2,500 CHP units with capacities between 100 and 300 kW have been installed in the Netherlands in hospitals, community buildings, schools, and businesses .

Unlike electricity, heat, usually in the form of steam or hot water, cannot be easily or economically transported long distances; therefore, typical CHP systems provide thermal energy for "local" services such as space heating or cooling, process heat, refrigeration, water heating, or local district heating. To make such systems viable, a sufficiently large need for heat must exist within a sufficiently dense area so that circulation of steam, hot water, or another appropriate medium is feasible and economic. CHP systems installed in a MicroGrid could capture two significant advantages over CHP systems in independent installations:

1. MicroGrid heat production is small scale and therefore can be well matched to requirements. That is, a MicroGrid should be constructed from the most economic combination of waste-heat-producing generators (e.g., high-temperature fuel cells and microturbines) and non-waste-heat-producing generators (e.g., windmills or PV modules) so that joint generation of electricity and heat is optimized overall. In other words, the total joint cost of supplying the

heat and electricity needs of the facility served by the MicroGrid should be minimized. End-use energy efficiency will play a critical role in maximizing the system energy efficiency.

2. In a MicroGrid, the production of heat can move close to its use. In an extreme example, a high-temperature fuel cell could be placed on each floor of a hospital to provide the hot water needs of the floor. Because electricity is more readily transported than heat, generation close to the heat load will usually make more sense than generation close to the electrical load. (The same principle holds with large power plants, which tend to be sited close to sources of cooling water but distant from the users of their power.) Because the MicroGrid permits small, diverse generators to operate in a passively coordinated manner, generators can be optimally placed relative to loads.

Low-Temperature Heat Use

The application that comes most readily to mind, as a useful waste-heat sink in small-scale, on-site generation systems is low- and moderate-temperature water heating. In the industrial sector, any number of applications is possible. In the commercial sector, the primary options are direct hot water use, e.g., restaurant dishwashing, sterilization, and space heating. Commercial hot water usage tends to be concentrated at a limited number of sites, such as hospitals and restaurants, which are promising hosts for power generation that would be delivered to neighboring MicroGrid customers that have minimal heat requirements, such as stores, offices, and residences. Some analysts have emphasized the potential for small-scale systems to serve the residential sector. Space heating requirements vary significantly by season, location, and building occupancy, so the economics of this CHP application are likely to be highly variable. Most hot water and space heating applications are fairly low-tech, so there are few technical barriers to widespread adoption.

Certain energy-generating technologies are more applicable to CHP applications. Microturbines, for example, offer higher-temperature heat output than reciprocating engines and thus can provide greater benefits in cogeneration applications. Two European manufacturers, Bowman and ABB, are specializing in CHP microturbines. In the U.S., Capstone is offering a package system that captures waste heat from their microturbine and allows it to serve thermal loads. High-temperature fuel cells also provide premium heat for CHP systems. There is vast potential for improving the system design of electrical and thermal energy services in residential and commercial applications. More work is needed in the area of MicroGrid system design and operation, especially in tools for determining the optimal placement of heat sources subject to constraints imposed by safety and noise concerns.

Picture of a Capstone Microturbine with an attached CHP unit. Source: Capstone Turbine **www.capstoneturbine.com**

CHP Technologies

A number of technologies are used for CHP systems. A typical CHP system of less than one MW capacity consists of the following items: a technology to generate power, an alternator for electrical output, a heat recovery unit to generate thermal energy, a component to evacuate combustion products (if necessary), a control system, an electrical- protection and low-voltage connection box, and soundproof insulation. The method used to recover heat in a CHP system depends on the type and capacity of the technology used to generate power. The power generation technologies that are likely to be usable for CHP in MicroGrids are reciprocating engines, microturbines, and fuel cells.

Reciprocating Engines

Reciprocating engines come in many types; the two designs that are most likely to be useful in CHP systems are four-cycle spark-ignited (Otto cycle) and compression-ignited (diesel cycle) engines. Otto cycle engines ignite an air-fuel mixture in a cylinder using a spark plug. Diesel engines compress the air in the cylinder, raising the ignition temperature of the fuel, which is injected at high pressure.

Reciprocating engines typically have electrical efficiencies of 25 to 50 percent. The smaller stoichiometric engines that require 3-way catalyst after-treatment operate at the lower end of the efficiency scale while the larger diesel and lean burn natural gas engines operate at the higher end of the efficiency range. In a reciprocating engine, energy from the fuel is converted into mechanical drive power and heat, which is released through the engine jacket and combustion gases. Engine jacket heat is removed by a cooling fluid loop. Approximately 60 to 70 percent of the total input energy is converted to heat that can be recovered from engine exhaust and jacket coolant. Heat dissipated to the engine jacket coolant accounts for about a third of the input energy and can reach temperatures around the boiling point of water.

A closed-loop hot water cooling system is typically used for capturing engine heat. The coolant is circulated through the engine passages and an external heat exchanger. These cooling systems can operate at about 90 to 120°C and use a heat exchanger to send excess heat to a cooling tower.

Ebullient cooling systems circulate boiling coolant through the engine and are often used for producing low-pressure steam. The coolant is limited to 120°C or saturated steam conditions. System benefits include extended engine life and improved combustion efficiencies as a result of the uniform coolant circuit temperature.

Engine exhaust is responsible for about 10 to 30 percent of fuel input energy, providing temperatures of about 450–650°C, although only a portion of the exhaust heat can be recovered because the gas must remain above condensation point to avoid corrosive condensation in exhaust piping. Thus, most heat recovery units are designed for a 150° to 177°C exhaust outlet temperature. This heat can then be used to generate 110°C hot water or low-pressure steam at 15 psig. The end result is that about 75 percent of the reciprocating engines input energy is utilized. The recovered heat can be used for CHP processes such as space heating, domestic hot water, absorption cooling, and desiccant dehumidification.

Microturbines

Microturbines have capacities from 30 to about 250 kW. For larger capacities, microturbines can be combined, which also increases reliability. Microturbine design is simple and often has only one moving part, a shaft with attached compressor, turbine, and permanent-magnet generator spinning at high speeds on air bearings. Microturbines operate at speeds up to 120,000 rpm and can be powered by a variety of fuels including natural gas, gasoline, diesel, and alcohol. Microturbines typically include a recuperator that preheats the incoming compressed air and increases electrical efficiency. Recuperators also cool the exhaust gas, however, and thus limit the thermal energy available for use in CHP applications. Most microturbine manufactures include a recuperator bypass value that reduces the electrical efficiency but increases overall system efficiency when waste heat is recovered. Microturbine efficiencies for power generation are typically about 30 percent, but the electrical efficiency falls to about half of that when the recuperator bypass is engaged although the overall thermal efficiency may rise to about 80 percent. The exhaust gas is typically at about 260°C while the recuperator is in use and 870°C when the recuperator is bypassed (E Source, 1996). Not all of the waste heat can be effectively transformed into useful energy.

High-temperature fuel cells can generate enough heat to produce steam for a steam turbine or microturbine, so combined-cycle power generation is possible, or waste heat can be captured by CHP, or both. Fuel cells operate by reverse hydrolysis, combining oxygen and hydrogen to produce electricity, heat, and water. Fuel cells produce DC current and heat using a chemical reaction rather than a mechanical engine driven by combustion and can operate as long as fuel is being supplied (in contrast to the fixed supply of chemical energy in a battery). Fuel cells can operate at electrical efficiencies of 40 to 60 percent (LHV), and up to 85 percent in CHP applications.

Some fuel cells release significant heat during operation; the quality of the thermal product depends on the type of electrolyte in the fuel cell. The phosphoric acid fuel cell (PAFC), which is commercially available, operates at moderate temperatures (approximately 200 °C) and produces low-pressure steam or hot water as a byproduct. Polymer electrolyte membrane (PEM) fuel cells are being developed primarily for transportation applications but may be used in stationary power as well. They operate at relatively low temperatures to protect the membrane and thus have the least potential for CHP applications. Two promising fuel cell chemistries, molten-carbonate (MC) and solid-oxide (SO) fuel cells, operate at much higher temperatures (650 and 900 °C, respectively) and are expected to provide excellent combined-cycle and/or CHP opportunities. SO fuel cells are based on all-solid ceramic construction and are expected to be a particularly reliable technology with electrical efficiencies up to 50 percent.

Heat Exchangers

Heat exchangers are designed from different materials depending upon their application. Stainless steel is expensive and does not conduct heat well but holds up effectively against the corrosion from exhaust gas condensate. Heat exchangers can capture about 80 percent of the heat from exhaust gas and transfer it to an absorption chiller.

Cooling Technologies

In buildings in most areas of the U.S., cooling is required in addition to (and frequently more than) heating; this weather-sensitive and often peak load imposes high costs on the centralized power system. For example, in California, air conditioning is estimated to be responsible for about 29 percent of peak electricity demand, yet this end-use only consumes about 7 percent of the state's total electrical energy. Refrigeration, though it is much less weather sensitive and has a high load factor, represents an even larger share of total electricity consumption in California, about 8 percent. MicroGrids will be able to effectively provide the electricity required by these major end uses; even more exciting is the possibility of waste heat being used to provide cooling. Absorption cooling and desiccant dehumidification are two techniques for using waste heat to meet or reduce cooling loads.

Absorption cooling uses heat (in place of the mechanical energy required to run a compressor) to drive a refrigeration cycle. Absorption cooling cycles take advantage of chemical processes using a refrigerant and an absorbent that combine at low pressure and low temperature to form a solution. Water and lithium bromide or ammonia and water (NH_3-H_20) are common refrigerant/absorbent combinations. The functioning of this technology is described using the example refrigerant/absorbent combination of water and lithium bromide: The absorber is kept at low pressure (0.1 Psia) so that the refrigerant (water) boils at 2°C. The refrigerant vapor is absorbed by the lithium bromide and becomes a saturated liquid, forming a solution and releasing heat during the saturation process. That is, the absorption process causes the refrigerant to become a liquid at under temperature and pressure conditions when it would normally be a vapor. The solution is then pumped to a device called a generator. The solution in the generator is at a higher pressure (0.9 Psia) and temperature (37°C) than on the absorber side of the cycle. Applying heat drives the refrigerant from the absorbent. The refrigerant passes through a filter, which keeps the absorbent on its side of the cycle, and into the condenser. The condenser is at the same temperature and pressure as the generator ; under these conditions, the refrigerant cools and becomes a liquid. It is then sprayed into the evaporator, where it expands to a gas because of the low pressure. As the refrigerant becomes a vapor, it picks up latent heat from its surroundings, producing a cooling effect.

Absorption cooling systems have been used for some time, but they are inefficient compared to compressors, typically having a coefficient of performance (COP) of up to 0.7 for single-effect chillers. The efficiency of these cycles is being increased by developments that permit the capture and use of more of the rejected heat from the cycle, with multiple cycles at lower temperatures. Methods of increasing the efficiency of absorption cooling by adding additional generators and condensers to utilize remaining heat from the primary generation process are called double-effect and triple-effect chillers and can have COPs of 1.1 and 1.5 respectively.

The fluid used as a heat input should have a temperature of about 90°C to drive a single-effect absorption chiller and temperatures between 120° and 150°C to drive a double-effect absorption chiller system. Absorption chillers are driven by hot water or steam from a rejected heat loop, or direct fired from a natural gas or propane burner. The direct-fired units are all double-effect systems because of, the high temperature of the gas (1200°C).

One major benefit of absorption cooling is that it can reduce the cooling load that often causes a customer’s daily and seasonal peak energy demand and is the most expensive load to meet. Even if the MicroGrid is not paying a true real-time price, lowering peak energy use may substantially reduce demand charges and provide immediate reductions in customers’ utility bills. Absorption cooling also allows more efficient and economical use of on-site generation and refrigeration and can provide a year-round use for the heat produced by electricity generation.

Desiccant dehumidification and cooling removes latent heat load (or moisture) from the air. This helps reduce cooling loads and allows air conditioning systems to operate more efficiently. Conventional cooling systems dehumidify the air by using a cooling coil that is cold enough to condense water out of the air. This requires more energy than would be required for sensible cooling alone. Desiccant systems can reduce heating, ventilating, and air conditioning (HVAC) electricity use by 30 to 60 percent and peak electricity demand by 65 to 70 percent (E Source, Space Cooling Technology Atlas, 1997). Payback periods for desiccant systems typically range from two to four years (E Source Tech Update, 1998).

Desiccant systems work by using a material that absorbs moisture from the incoming air flow. The desiccant is then rotated to a warm air stream to be heated and dried. DER can provide a source of heat for desiccant systems and can thus help reduce the energy use of the cooling system.

Cost of desiccant systems have been prohibitive in the pats but are declining and in some applications are offset by the savings from reduced cooling costs. The economic benefit of desiccant dehumidification is a function of the particular application and the potential benefit from humidity control, and the summer humidity level and the electricity tariffs in a given area. Desiccant systems are suited for applications where humidity control is important. These include museums, supermarkets, hotels, hospitals, some industrial facilities, and other types of buildings in humid areas.

APPENDIX B. Electrical Environment for MicroGrids

B. 1 Interconnection Issues

DER has gained increased attention as electrical power supply and demand issues have become more urgent. At the center of these issues is the need for additional power generation and the ability to transmit greater amounts of power to end users. Historically, investments in infrastructure -- new generation and associated transmission and distribution (T&D) systems -- have followed expanding power needs. However, in recent years these investments have not kept pace with rising demand, resulting in shrinking reserves and transmission systems operating near their limits. During the same time period, advances in technology have substantially reduced the cost of DER, so, for the first time, they are being seriously considered as a solution to growing power needs.

DER consist of many electric power resources distributed throughout lower-voltage power distribution systems. These resources are typically small generators, but they can also be energy storage devices or non-conventional power sources such as PV or fuel cells. As implied in the definition, the power produced by DER does not travel over the high-voltage transmission grid prior to being delivered to end users. In most cases, DER are located very close to the power loads it serves, but power from DER could be injected into the lower-voltage distribution system. In principle, this power could make its way into the high -voltage electrical transmission system, but, in practice, it typically serves loads in near its point of generation.

Current Integration Standards for DER

Local interconnection standards vary considerably from one utility to the next. A national standard is being drafted by the IEEE SC21 working group. ANSI standard P1547 (Draft) Standard for Distributed Resources Interconnected with Electric Power Systems does not use the term "MicroGrid," but it addresses a group of DER as a Local Electric Power System (LEPS). The standard accounts for the issue of a LEPS connecting to the utility grid (Area Electric Power System or AEPS) by focusing on the aggregate DER rating of the LEPS. As a result, the rules applied to a MicroGrid containing many small DER are the same as for a single large distributed energy source. P1547 applies only to single or aggregate DER of 10 MVA or smaller. Although IEEE draft Standard P1547 allows safe and reliable integration of DER into radial distribution systems with minimal immediate economic costs, it does not provide a means for DER to operate separate from the utility grid.

System Protection

A typical radial distribution system has been assumed in the discussions that follow; we also assume that DER are integrated with this distribution system in accordance with IEEE draft P1547. The changes that would be required in existing protection schemes are outlined below.

Transformer Protection:

- Transformer Fault: Connecting the MicroGrid to a utility grid would not affect the ability of the utility's differential protection scheme to detect and/or isolate a transformer fault. No adjustments to this protection would be necessary.

Line Protection:

- Ground Fault on the Feeder: DER that are connected to the faulted phase would contribute to the fault and thus reduce the fault current seen by the AEPS. However, at the inception of the fault, all but the lowest rated DER (on all phases) would detect the fault and separate from the system per IEEE P1547. After the DER separate, the fault current contribution from the AEPS would increase and feeder protection would enable, just as though DER had never been connected to the feeder. The fault detection time might be prolonged because of the presence of DER, but the protection scheme would not need to change. IEEE P1547 would require DER to comply with local rules regarding reclosing coordination. A reasonable approach for this coordination would be for the utility to require DER units that have tripped off line to remain off line for a period of time that exceeds all disturbance and reclosing events (e.g., five minutes). These requirements would have little impact on existing system protection.
- Line-to-Line Fault on the Feeder: For DER connected to the faulted line, the voltage seen at the DER terminals would, in most cases, be out of the allowable operating band specified in P1547, so the DER would trip off line. DER operating on the unfaulted phase during a line-to-line fault would, in most cases, also exhibit voltage outside of the allowable operating band specified in P1547 and would thus trip off line. If the unfaulted phase voltage did not move outside the allowable operating range, detection of the fault by the utility would not be impeded by operation of DER. Thus all phases of the feeder would be tripped per the utility’s normal protection scheme. At that point, all DER that remained connected would sense voltage outside of the allowable operating range and would immediately disconnect.

Voltage Regulation

Many distribution transformers include load tap changers (LTCs), which adjust the transformer's turns ratio based on the load current and thus influence voltage regulation. As DER units were placed on line or off line, the LTC would see more or less current and adjust the transformer's voltage output to compensate for the voltage drop of the feeder. If DER were sited away from the LTC, then, as the DER were turned on, the feeder's voltage profile would benefit by flattening out. However, if DER were located very close to the LTC, they would have an undesirable effect on the feeder's voltage regulation, which would have to be remedied by adjustments to the LTC or by other means. For distribution systems that do not use LTCs, the integration of DER might cause voltage regulation problems that would need to be addressed by a permanent tap change to the distribution transformer, the addition of an LTC, or other means. However, if the MicroGrid is designed correctly, the voltage at the interfacing point will be constant over a large range of loads and should greatly reduce the problems of LTCs.

Next-Generation Distribution Systems

Although the IEEE standard permits integration of single DER into radial distribution systems, it does not allow all of the potential benefits of DER to be realized. The benefits that would not be possible under the standard as it is currently drafted include:

- Increasing system reliability by relying on power supplied to customers by both DER and the transmission grid (because P1547 requires DER units to disconnect from the utility when a disturbance occurs),
- Allowing the aggregate load within a distribution system to exceed the rating of its interconnection to the transmission system,
- Regulating voltage by utilizing DER voltage control,
- Enhancing system stability by providing reactive power support to loads within the distribution system,
- Permitting "islanded" operation, which would allow sections of a distribution system to continue operating at the same time that a faulted section is isolated.

The MicroGrid is designed to provide all of these benefits to its own customers in addition to meeting the above restrictions for the distribution system.

Distribution Area Monitoring and Control

Integrating DER so that they can provide the benefits outlined above will require overhauling the conventional distribution system so that it functions similarly to the traditional transmission system. The key ingredients of this overhaul would be as follows:

<u>Frequency Supervision</u>: When DER separate from the transmission grid, no frequency "leader" exists for them to follow. Therefore, a real-time, global signal must be sent to DER to constantly set and synchronize the frequency at which they generate power.

<u>Dispatch Control</u>: In any closed power system, the power generated must equal the power used. Controllers or governors can control the power generated up to a point beyond which more available generation must be dispatched to meet demand. A control system is needed to automatically dispatch generation when system load approaches available generation.

<u>Load-Shedding Control</u>: If demand exceeds all dispatched generation, loads must be de-energized or the system will become unstable. A controller is needed to systematically de-energize loads when sufficient generation is not available for dispatch.

<u>Voltage and Reactive Power Support</u>: DER must establish and support system voltage. Voltage support is needed to regulate voltage throughout the distribution system. Reactive power control is also needed to ensure system stability.

<u>Synchronizing capability</u>: An isolated distribution system must be able reattach to an energized transmission system without an interruption in service. Likewise, isolated DER must be able to reattach to an energized distribution system.

Dynamics Management: If MicroGrids are to operate isolated from the utility grid, they must have sufficient means to stabilize system disturbances. Typical power systems automatically store energy reserves in their rotational kinetic energy, which can absorb energy from or add energy to the system. However, most DER within a MicroGrid are expected to be based on power electronics, so they will have no rotational kinetic energy. When a disturbance occurs in an isolated MicroGrid, the system is constrained to match generation with loads. Without a power repository equivalent to system inertia, the MicroGrid would need to correct this mismatch in such a way that further system voltage or frequency suppression would result, leading to loss of loads and instability of the system. Although the rotating loads within a MicroGrid do have inertia, the loads themselves will likely be insufficient to mitigate these dynamic concerns. Ensuring that MicroGrids maintain system stability will not be a matter of simply following past practice.

B.2 Customer Systems

Customer systems can contain DER connected to a 35-kV, 25-kV, 13.8-kV, or even 2.2kV distribution system. It includes step-down transformers and a 480-V or 208-V system (secondary distribution system) that may be radial or networked. A single-line diagram of a radial system is shown in Figure B2.1. A single-line diagram of a networked system is shown in Figure B2.2.

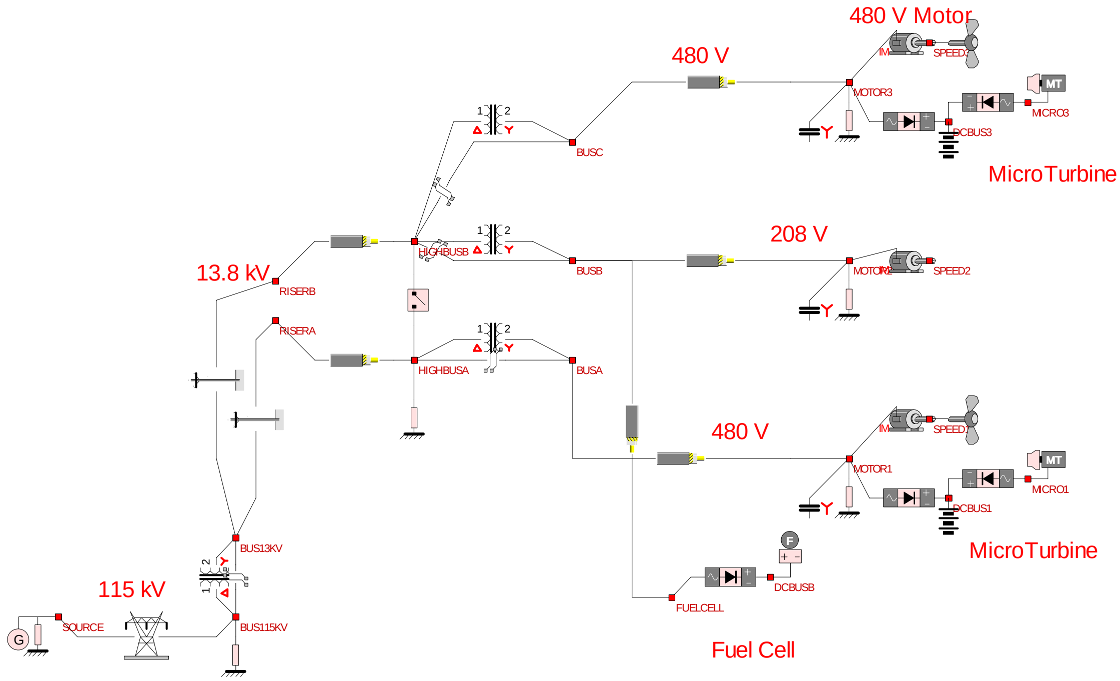


Figure B2.1 Conceptual Single-Line Diagram of a Radial MicroGrid

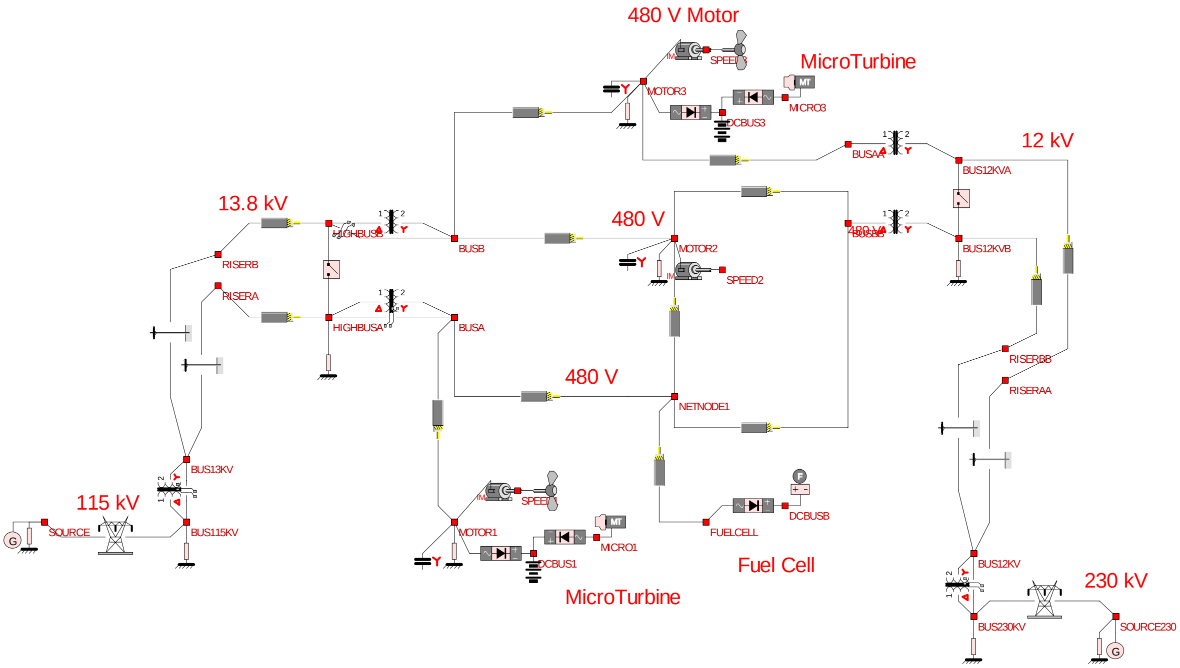


Figure B2.2 Conceptual Single-Line Diagram of a Networked MicroGrid

B.2.1 MicroGrid Topology

MicroGrid topology may be dictated by current design practice for secondary distribution systems. There are two approaches, radial systems and networked systems that have different design, protection, and operational requirements.

Networked secondary systems are uncommon; they are operated by a few utilities in areas of concentrated loads, e.g., New Orleans, New York, and have the 480- or 208-V circuits connected in a network and supplied by network transformers. Network transformers are special transformers with “network protectors” that permit the flow of power only from the high side to the low side. Microsources may be connected anywhere on the 480- or 208-V system. The advantage of this configuration is that the microsources are connected to a network, so the network’s protection philosophy can be adopted for the microsource and the microsource can supply power to all loads on the system. This allows MicroGrid operation to be controlled over a wide range of load/generation within the constraint of one- way power flow in the network transformers. This configuration is important because there is a wealth of information on how to operate network secondary distribution networks, which can be used for MicroGrids.

A MicroGrid may have three-, two-, or single-phase connections to the utility distribution system. The various possibilities are shown in Figure B2.3. The main circuit is a five-wire system with three phases, a neutral, and a ground conductor. The ground conductor is grounded at multiple points, and the neutral is grounded at the source end of the circuit. Part of the MicroGrid may be connected to the utility distribution system by three-phase transformers (typically delta-wye connected, delta on the utility side), and part of the MicroGrid may be two phase or single phase. Two-phase and single-phase systems are generated from tapping to the utility distribution system phase-to-neutral or phase-to-phase. The exact connections are described in the sections below on wiring practices and grounding and bonding.

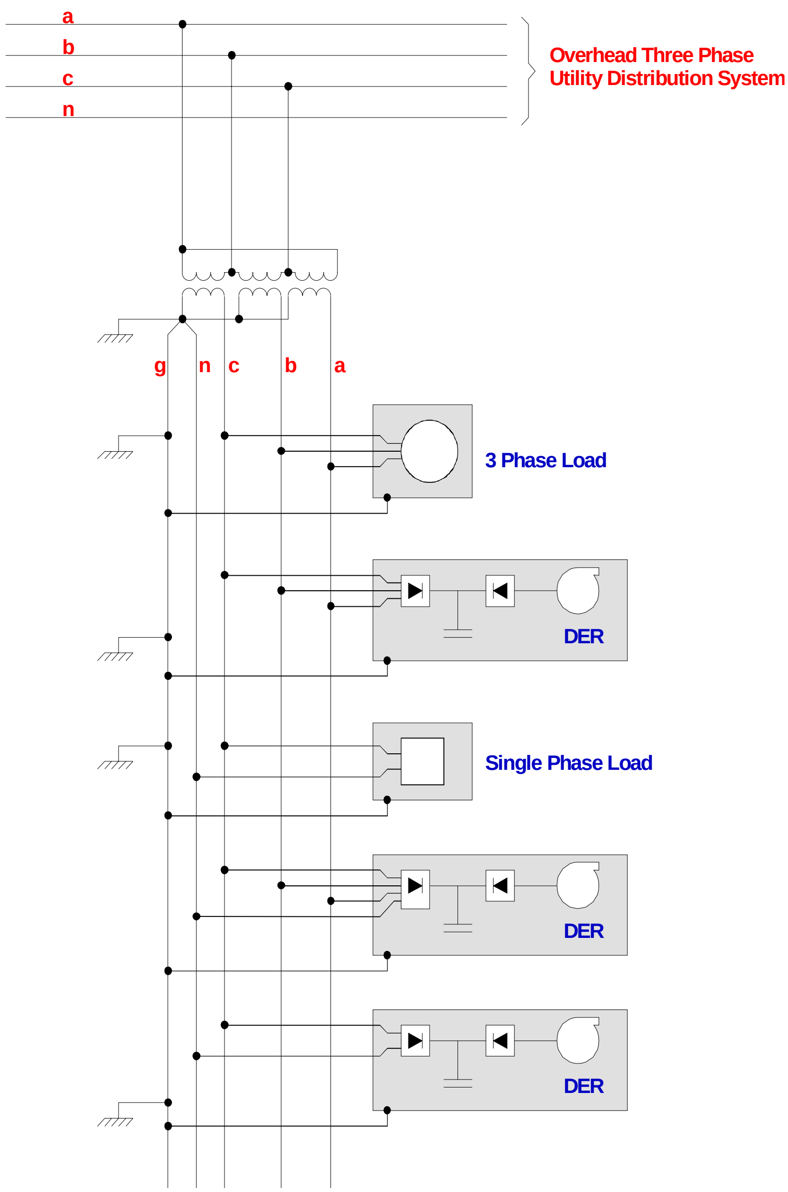


Figure B2.3 Illustration of Possible MicroGrid Topologies

Wiring Practices

Wiring practices for secondary distribution systems are dictated by the National Electrical Code and prudent engineering design. For three-phase systems, the best practice is a five- wire, three-phase circuit with a neutral and a ground conductor. If metallic conduit is used, the ground wire may be omitted, or, if the ground conductor is included, it may be bonded to the conduit. The size of the phase conductors and neutral are selected based on the rated amperage of the device. The neutral is normally the same size as the phase conductors or one size smaller. In cases of substantial imbalance or substantial zero sequence harmonics, it may be necessary to have a neutral that is larger than the phase conductors.

Grounding and Bonding

Grounding arrangements depend on the number of wires and voltage transformations. Figure B2.4 illustrates a system with two voltage transformations; Figure B2.5 illustrates a system with one voltage transformation. The National Electrical Code and good engineering practice require that the system be grounded at least once for each derived system. A derived system is generated with a voltage transformation. Each derived system can be a three-wire system (three phases only), or a four-wire system (three phases and a neutral, or three phases and a ground conductor), or a five-wire system (three phases, a neutral, and a ground conductor). Typical practice dictated by the National Electrical code, is to ground the neutral conductor at the source location. If a ground conductor is used, it should be grounded at multiple points. The National Electrical code permits the neutral conductor to be grounded at more than one location in specific cases.

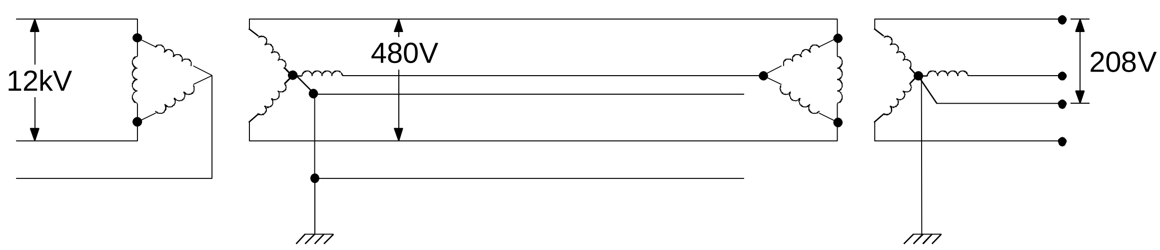


Figure B2.4 Distribution System with Two Voltage Transformations

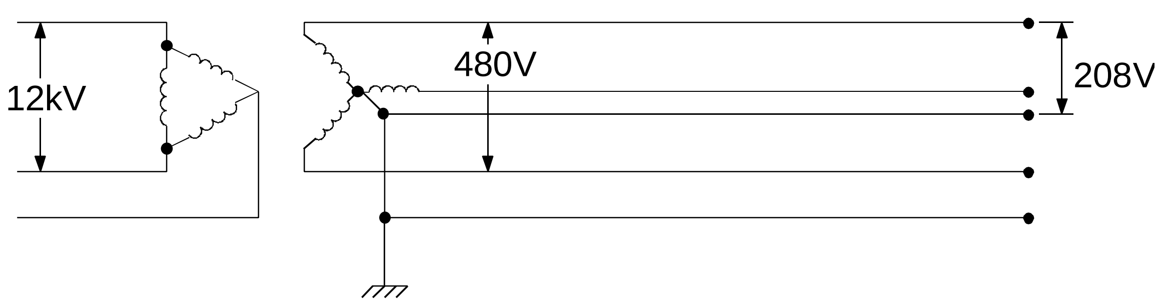


Figure B2.5 Distribution System with One VoltageTransformation

Standards

The applicable standards for customer systems are: the National Electrical Code, the National Electrical Safety Code, IEEE Std 80, FIPS Pub 94, Standard P1100, and draft standard 1547. Additional standards cover specific issues related to secondary distribution systems.

B2.2 Unbalanced Voltages and Loads, Stray Currents and Voltages

Customer loads may be three phase or single phase. Single-phase loads are typically connected phase to neutral, which generates voltage imbalances. The presence of induction motors can amplify imbalances. To minimize imbalances, induction motors should be on separate circuits if possible. Techniques for controlling imbalances and stray voltages and currents in conventional systems consist of: using a transformer as a buffer between the system and the imbalance generating load, increasing the size of the neutral, and enhancing the grounding system and therefore decreasing the ground impedances. MicroGrids provides an added opportunity for controlling imbalances and stray voltages and currents. The possibility of using DER to mitigate these problems will be discussed below.

Sources of Imbalance

The sources of imbalance in a MicroGrid are single-phase loads, distorting loads, and circuit asymmetries.

It is well understood that single-phase loads make three-phase currents unequal. The unbalanced currents generate unbalanced voltages because the voltage drop in the various phases will be unequal.

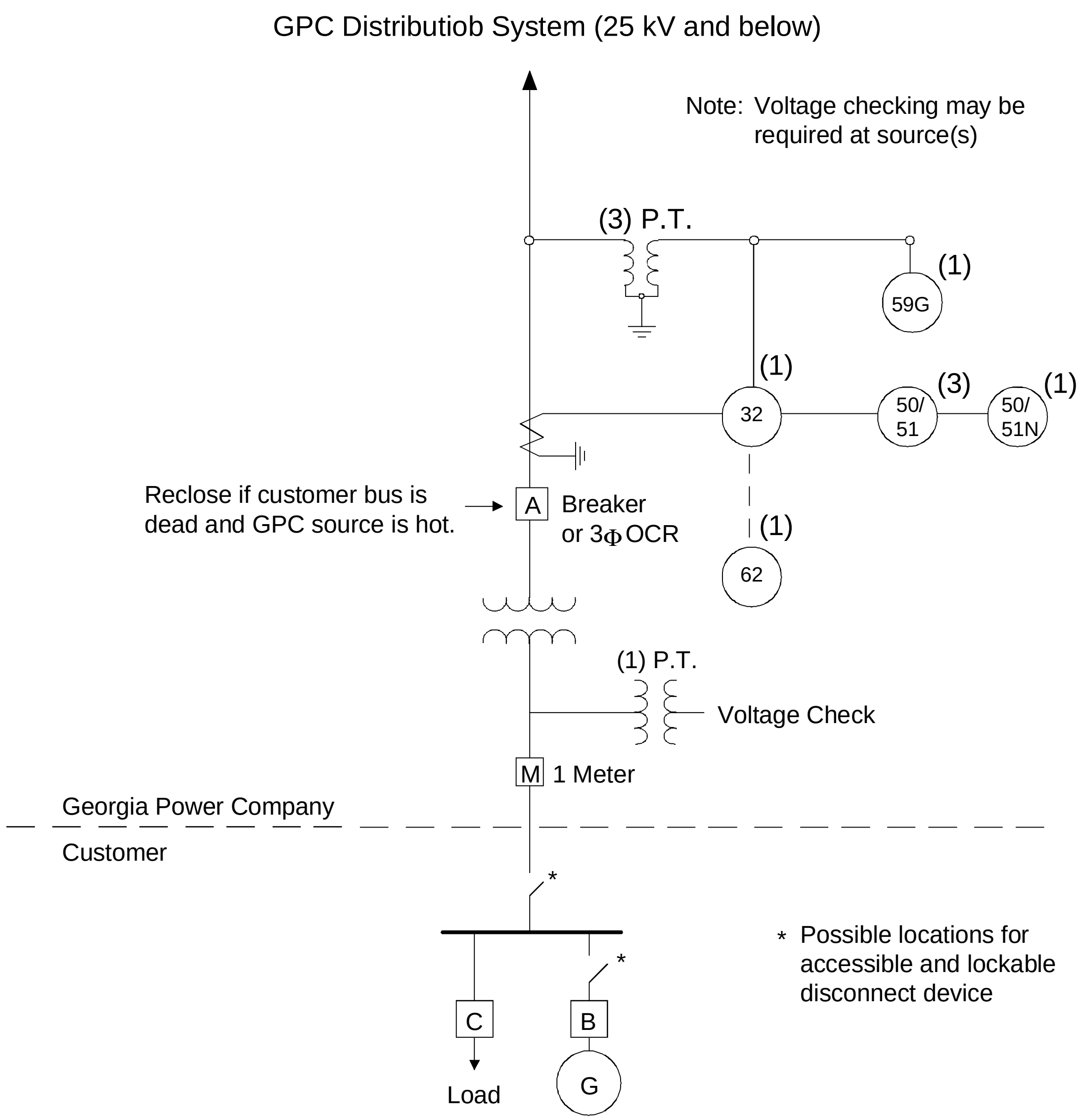
In secondary distribution circuits (480 V or 208 V) it is common to have loads that distort the sinusoidal waveform of the voltages and currents; i.e., they generate harmonics. The harmonic currents generated by distorting loads are often not of positive sequence (i.e., balanced currents). Most distorting loads may generate negative and/or zero sequence harmonics. Both negative and zero sequence currents contribute to the system imbalance.

Finally, circuit asymmetries generate imbalances in the system. A circuit is asymmetric if the flow of a balanced set of electrical currents through it generates three-phase voltages that are unbalanced. Most practical circuits are asymmetric. The degree of imbalance in a typical practical system may be up to six percent, measured as the percentage difference among the three phases. Attention to the placement and arrangement of the three phases can minimize the asymmetry of the circuit and the resulting imbalance.

In a typical customer system, all three sources of imbalance are present. The relative degree of the imbalance and the specific contributions from each source depends on the system.
Effects of Imbalance on End-Use Equipment
The effects of imbalance on end-use equipment are uneven phase heating and accelerated aging of the equipment, and interference with the controls of intelligent devices such as converters and relays.

Uneven phase heating

Uneven heating of the three phases occurs when the electric current magnitude is different in each phase. In this case the device must be derated for the purpose of keeping its maximum operating temperature within its specifications. This effect can occur in cables, motors, transformers, etc. The required derating is computed on the basis that the ohmic losses in any one phase of the device will not exceed the rated losses. In certain cases, the interaction of the imbalance and the device operation result in increased electrical current imbalance. In this case, the current in the three phases of the device may be much more unbalanced than the imbalance in voltage. Induction motors have this characteristic; a small voltage imbalance in an induction motor may result in a much larger current imbalance and therefore substantial derating of the motor. As an example, Figure B2.6 shows a typical customer system with induction motors. Figure B2.7 illustrates the terminal voltages and current for the motor that is located in the lower right corner of Figure B2.6. Note that the terminal voltages have a 1.94 percent imbalance, and the electric current imbalance is 6.17 percent. This operating condition will result in an eight percent derating of the induction motor.



Device No.	Function	Trips
32	Reverse Power	Starts Timer 62
62	Timer for 32	A
59G	Zero Sequence Overvoltage	A
50/51	Phase Overcurrent	A
50/51N	Ground Overcurrent	A

Figure B2.6. Interconnection Requirements Defined by Georgia Power Company in their Document "Guide for Interconnection Requirements and Parallel Operation of Customer Generation (Courtesy of Georgia Power Company).

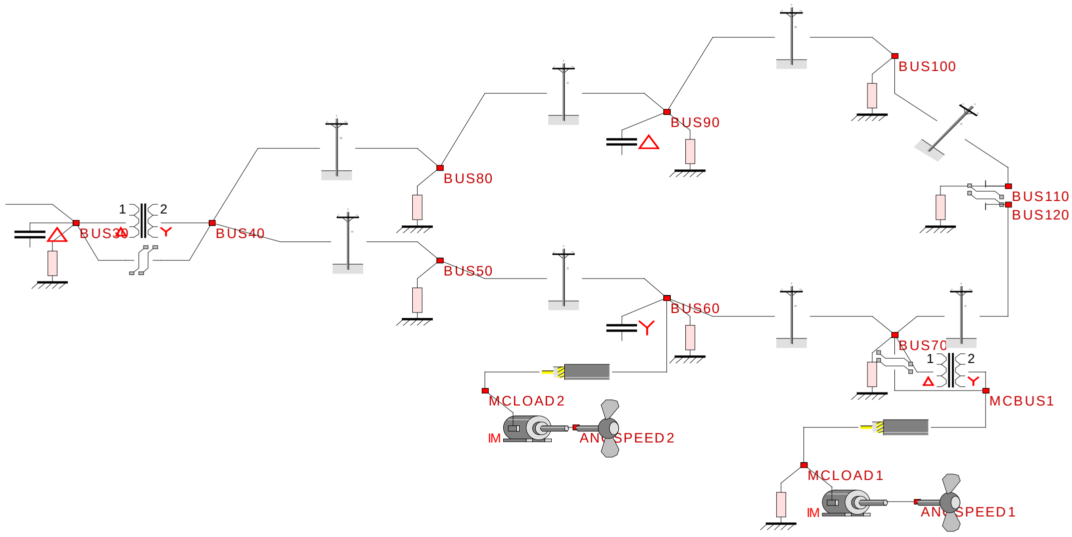


Figure B2.6 A Customer System with Induction Motors

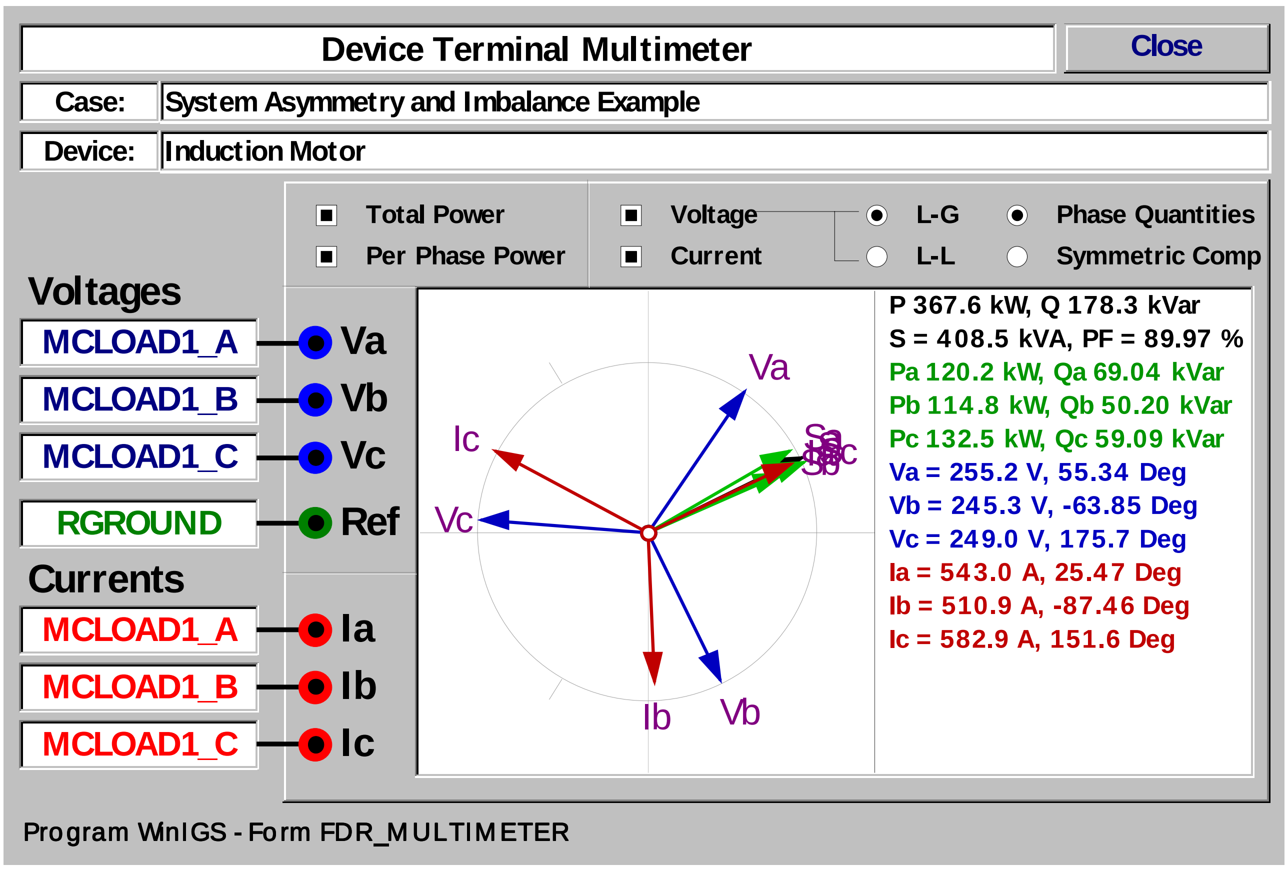


Figure B2.7 Illustration of Uneven Induction Motor Loading because of Imbalance

Interference with controls
Much new electronic equipment monitors imbalances and interrupts operation when an imbalance exceeds a certain level. This is very important for MicroGrid operation because most current products are designed so that inverters and therefore microsources will be disconnected when imbalances exceed a certain threshold.

Imbalance Mitigation Methods

There are many ways to mitigate imbalance. Below we summarize some key strategies, but this discussion is not exhaustive.

Load balancing
Load balancing entails distributing single-phase loads to the three phases in such a way that each phase will have approximately the same amount of load. Because, in general, electrical loads are not very predictable, the method does not always effectively balance the three phases.

Use of transformers
Connecting single-phase loads to two phases using transformers, as shown in Figure B.2.8, minimizes imbalance. In this case, the single-phase load current is converted into positive-sequence and negative-sequence current that reduces imbalance as compared to a direct, single-phase connection. Using transformers in combination with load balancing is an effective way to mitigate imbalance. In general, insertion of a transformer, three phase or single phase, tends to mitigate imbalance.

Circuit symmetry
Use of symmetric circuits also minimizes imbalance. Circuits can be made symmetric by twisting the three phases continuously and/or making sure that the three-phase arrangement is symmetric(for example, a triangular arrangement with the neutral in the middle).

Stray Currents and Voltages

Imbalances generate electric current flow in the soil because the distribution system and MicroGrid are grounded at multiple points; therefore, whenever there is imbalance, some of the unbalanced current will flow into the soil. Specifically, in systems with multiple ground neutrals, the grounds connect the neutral in parallel with the earth. (The National Electrical Code permits the grounding of a neutral in more than one place under certain conditions). In this case, any unbalanced current that may flow in the neutral will partially return through the earth. Practitioners refer to the currents that flow in the earth as stray or objectionable currents. The advantage of this grounding arrangement is that the overall impedance of the parallel combination of neutral and earth paths and ground conductors is lower. Stray or objectionable currents are harmless if the system is properly designed The only disadvantage is that this effect interferes with ground fault protection.

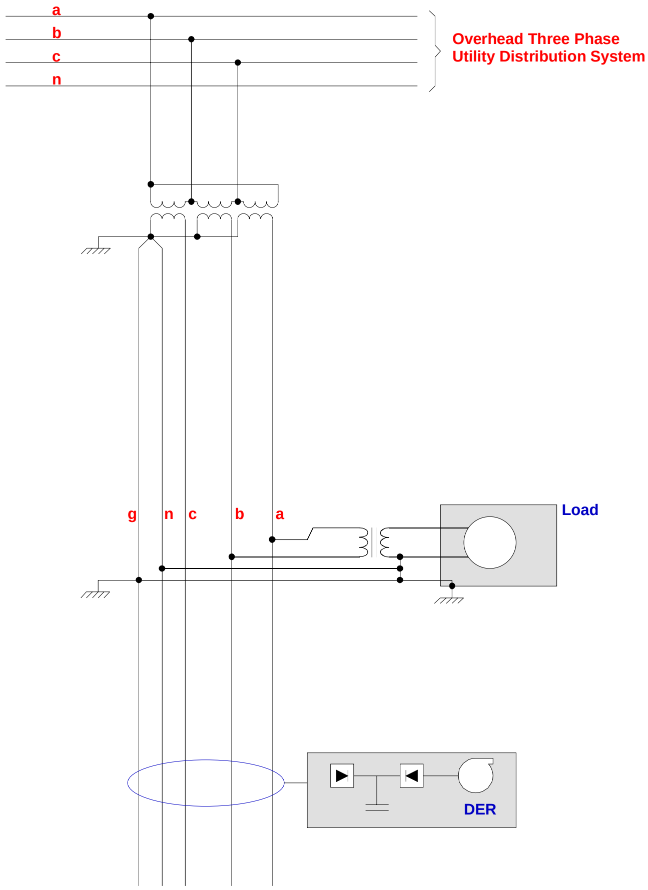


Figure B2.8. Use of Transformers to Mitigate Imbalance

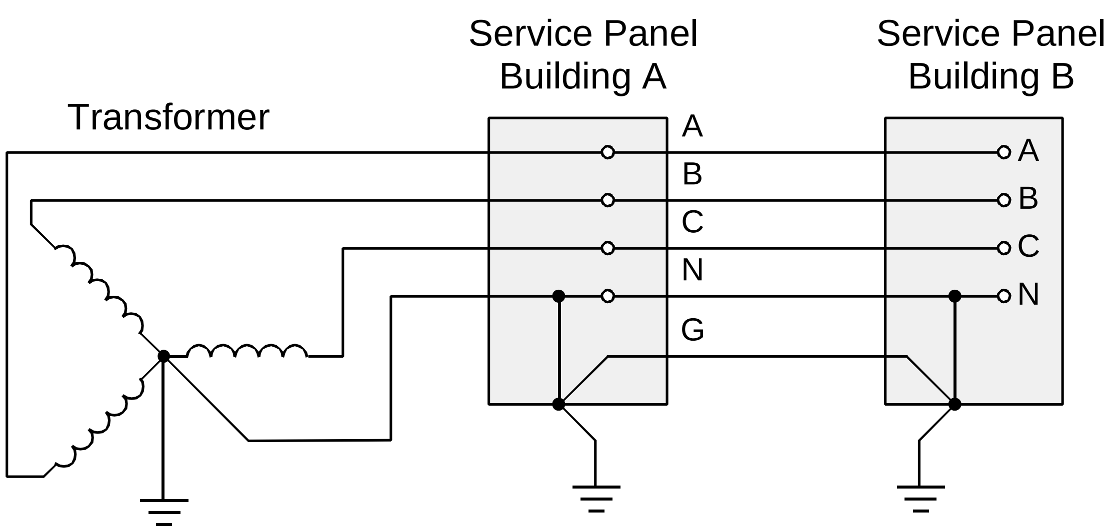


Figure B2.9. Illustration of Stray Voltages and Currents Generation

B2.3 Power Electronic Interactions

Customer systems may have complex interactions with power electronic devices. The level and effects of interaction depend on the dynamics of the customer system. One way to characterize customer systems is by frequency scans that determine the impedance of the system at a specific point as a function of frequency. Frequency scans reveal that customer systems are in general asymmetric; i.e., the impedance of one phase may be quite different from the impedance of another, as described below. Asymmetries can generate non-characteristic harmonics resulting from the interaction of converter controls and the system. The power electronic interface of DER can be used to control and mitigate these interactions, which depend on system impedances as a function of frequency. Customer systems may also exhibit a number of harmonic resonances. The presence of harmonic resonance conditions may amplify the interaction of inverters and the system. In a typical system there may be multiple harmonic frequencies.

System asymmetries can be revealed by frequency scans of each individual phase. For a symmetric power system, the impedance of a specific phase versus frequency will be the same for each one of the three phases. An asymmetric system will display differences. As an example, Figure B2.10 provides the frequency scan for a typical customer system of phases A and B of a specific three-phase bus. This system is quite asymmetric. The indicated impedance at 123.2 Hz is 0.7537 ohms for phase A and 0.7115 ohms for phase B, a difference of about six percent. This asymmetry will affect the performance of the power electronic interface of DER.

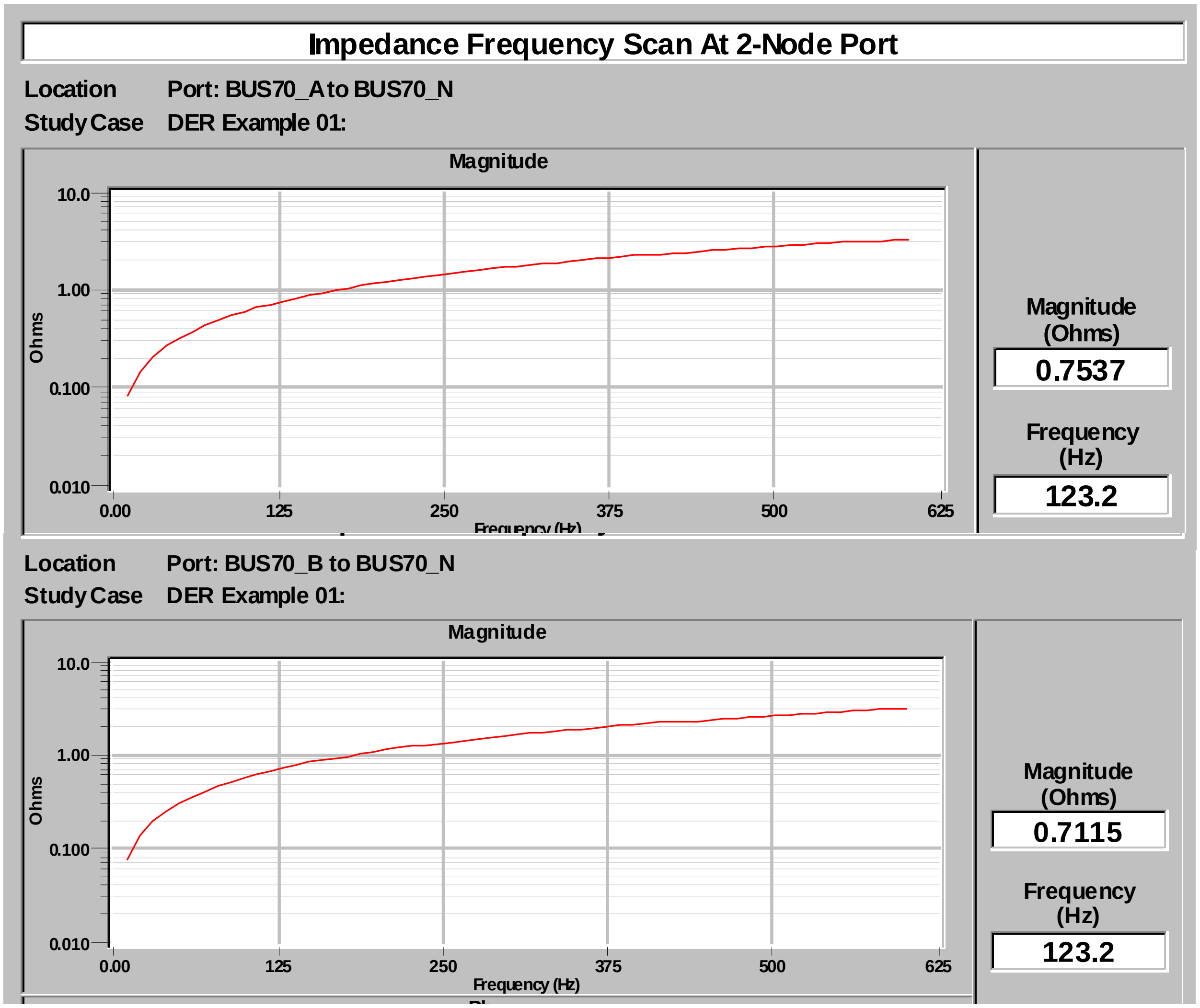


Figure B.10 Frequency Scans of Phases A and B for a Typical Customer System

Network-Converter Interactions

DER interface with the customer system using inverters. Each inverter takes feedback from the AC side by monitoring of voltage zero crossing. More sophisticated inverter controls may monitor the positive-sequence voltage at the interface bus to provide a reference. In both cases, imbalance in the voltage that may result from circuit asymmetries or asymmetric electrical loads will lead to imperfect operation of the inverter because of a small shift in the reference. This condition has been shown to generate additional distortion to the voltage waveform. Use of pulse width modulation can minimize the effects of network-converter interactions. In a MicroGrid, a relatively large number of converters could be connected to the customers' systems. In this case, there may be interaction among the controls of the various converters and amplification of the ensuing dynamics. This issue needs further research.

Harmonic Resonance

The power electronics of a typical microsource will generate some harmonics. In addition, customer loads may disturb waveforms and thus generate harmonics. Because circuits may include inductance and capacitance, resonance is possible. When the resonance frequency coincides with a harmonic frequency, any injection of harmonics at this frequency will be amplified somewhere in the system. The severity of the condition can be determined by the value of the resonance Q; the larger the Q value, the more severe the amplification will be. Q can be computed with frequency scans (Bode plots). Figure B2.11 illustrates an example system. The frequency scan at phase A of BUS70 is shown in Figure B2.12. Strong resonance can be seen at around 335 and 430 Hz. Q can be determined from this figure.

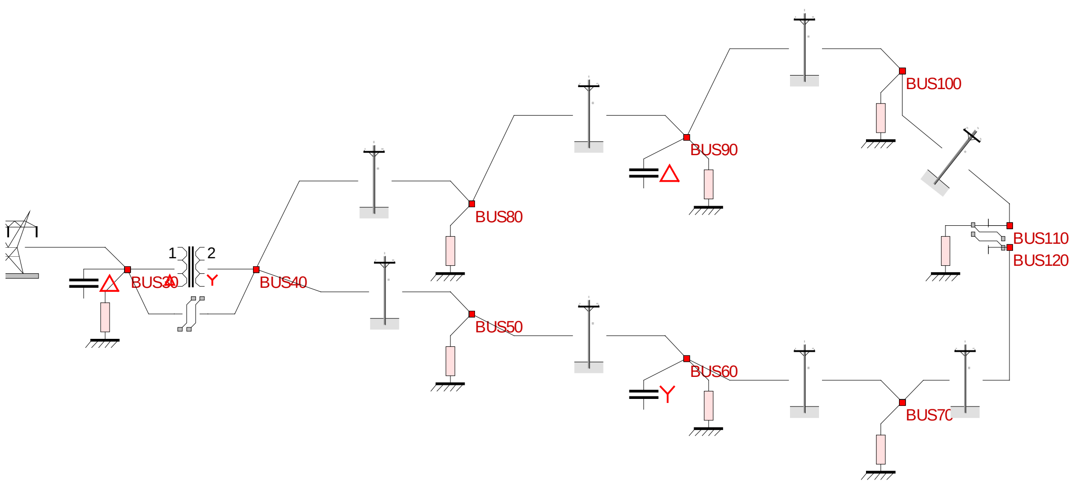


Figure B2.11 A Typical Customer System

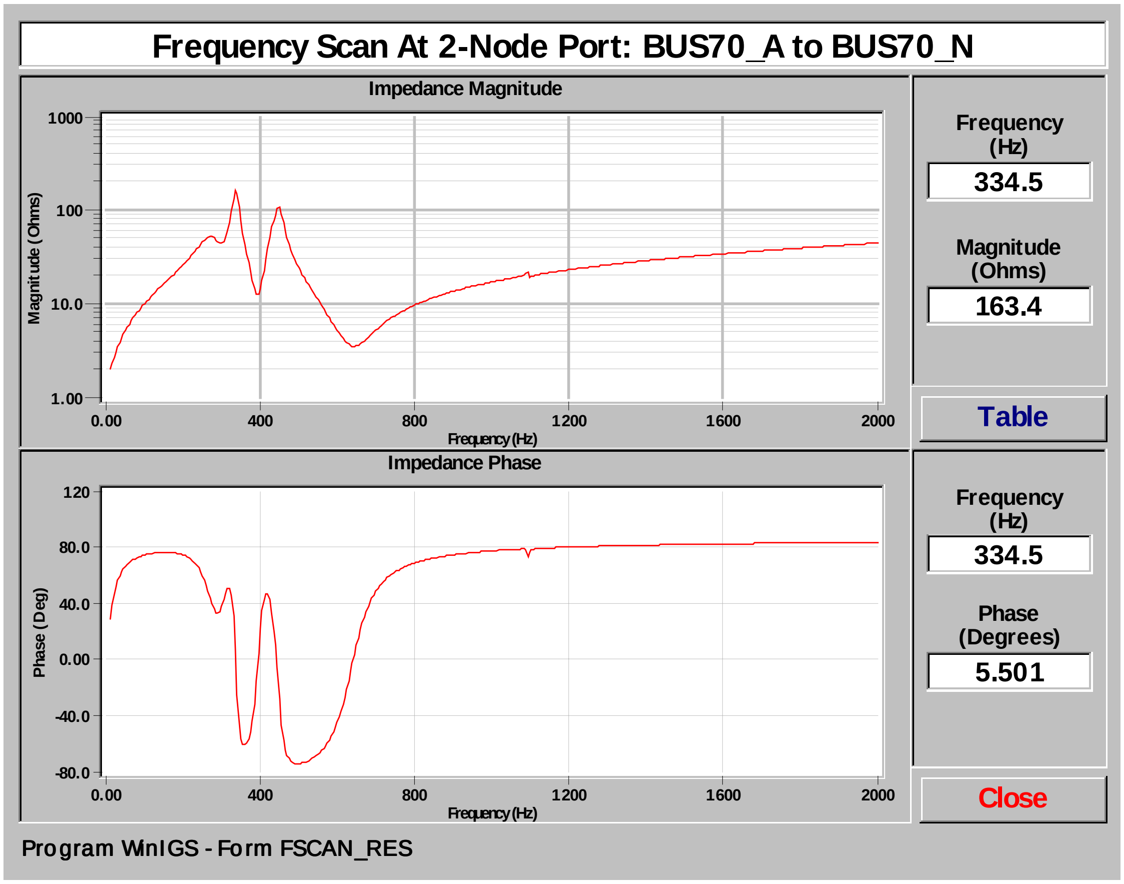


Figure B2.12 Frequency Scan at BUS70 of the System of Figure B2.11

B2.4 Voltage Drop, Reactive Power Demands, Circuit Losses, and Induction Machines

This section addresses voltage drop, reactive power, circuit losses and specific requirements of induction motors on a conventional distribution circuit. Industry practices to minimize voltage drops, improve power factors, and minimize losses are described. The impact of DER and possible ways that DER can be used to improve the performance of the distribution system with respect to these issues are also discussed.

Secondary distribution systems operate at the two standard voltages, 480 and 208 (line to line). At these voltages, the currents for typical loads are relatively high, so the voltage drop along the circuits is relatively high as compared to the nominal voltage.

Voltage Profile

The voltage profile of a customer system
depends on the wire size, circuit length, and load distribution. Typical customer systems have circuits with relatively short lengths to minimize the voltage drop along each and therefore improve the voltage profile. Network systems have better voltage profile performance.

Effects of DER

The presence of DER can benefit a system's voltage profile especially if the DER are placed at strategic locations. DER affect voltage profile in two ways: by modulating the loading of the circuit (i.e., the current level in the circuit is decreased if a microsource is placed at the appropriate location) and by injecting reactive power that can boost or control the voltage magnitude, just as a capacitor is used to increase the voltage magnitude in an AC circuit.

Three figures below illustrate the effects of a microsource on a system's voltage profile. Figure B2.13 shows the voltage profile of a typical customer system. Figure B2.14 illustrates the same system's voltage profile when a microsource is added at a specific location; it is assumed that the microsource is operated at unity power factor. Figure B2.15 illustrates the same configuration as the previous figure but with the microsource operated at 0.90 power factor current leading. Note that the system voltage profile of the system improves in each succeeding figure. The operation of the distributed energy resource at unity factor improves the voltage drop from 0.4 kV to 0.3 kV, a 25 percent improvement. The same microsource operated at 0.90 power factor (current leading) with all other system details remaining the same improves the voltage drop from 0.4 kV to 0.19 kV, a 53 percent improvement.

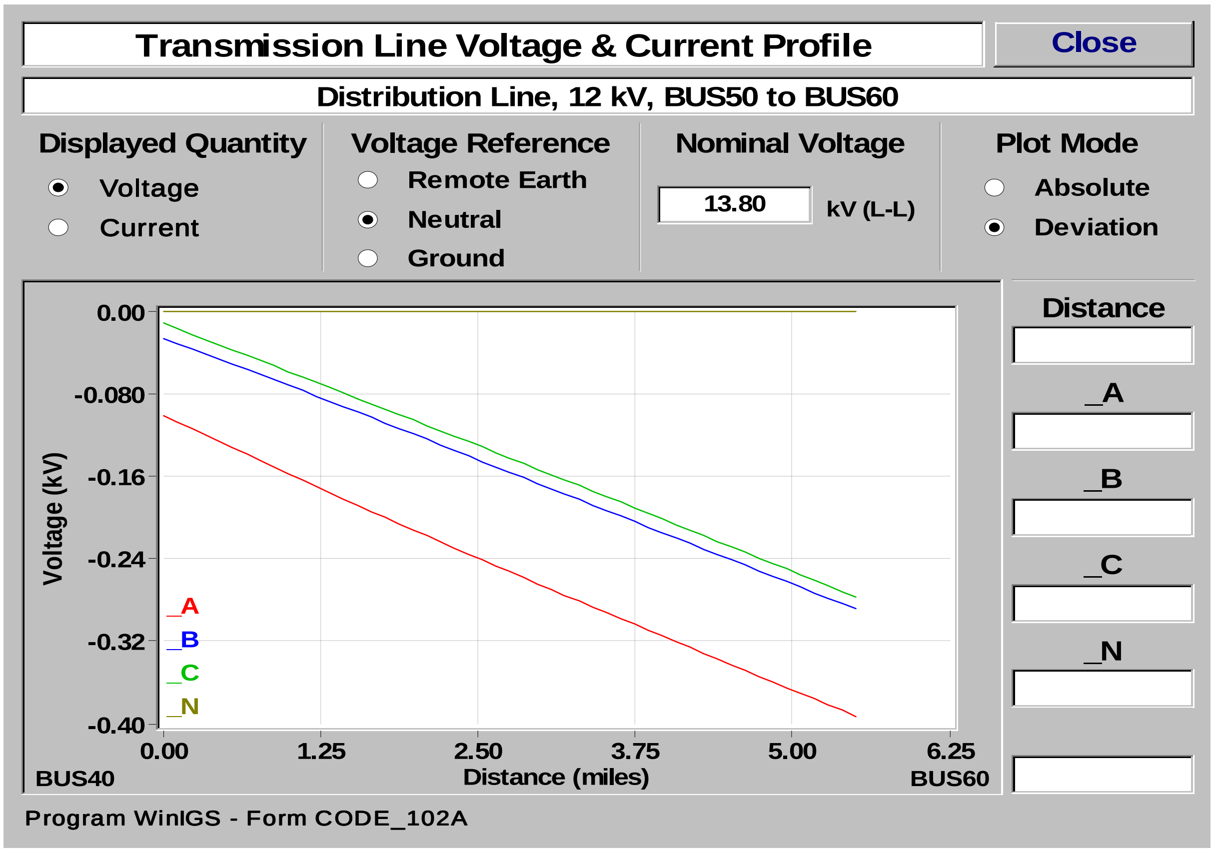


Figure B2.13. Voltage Profile of a Typical Customer System

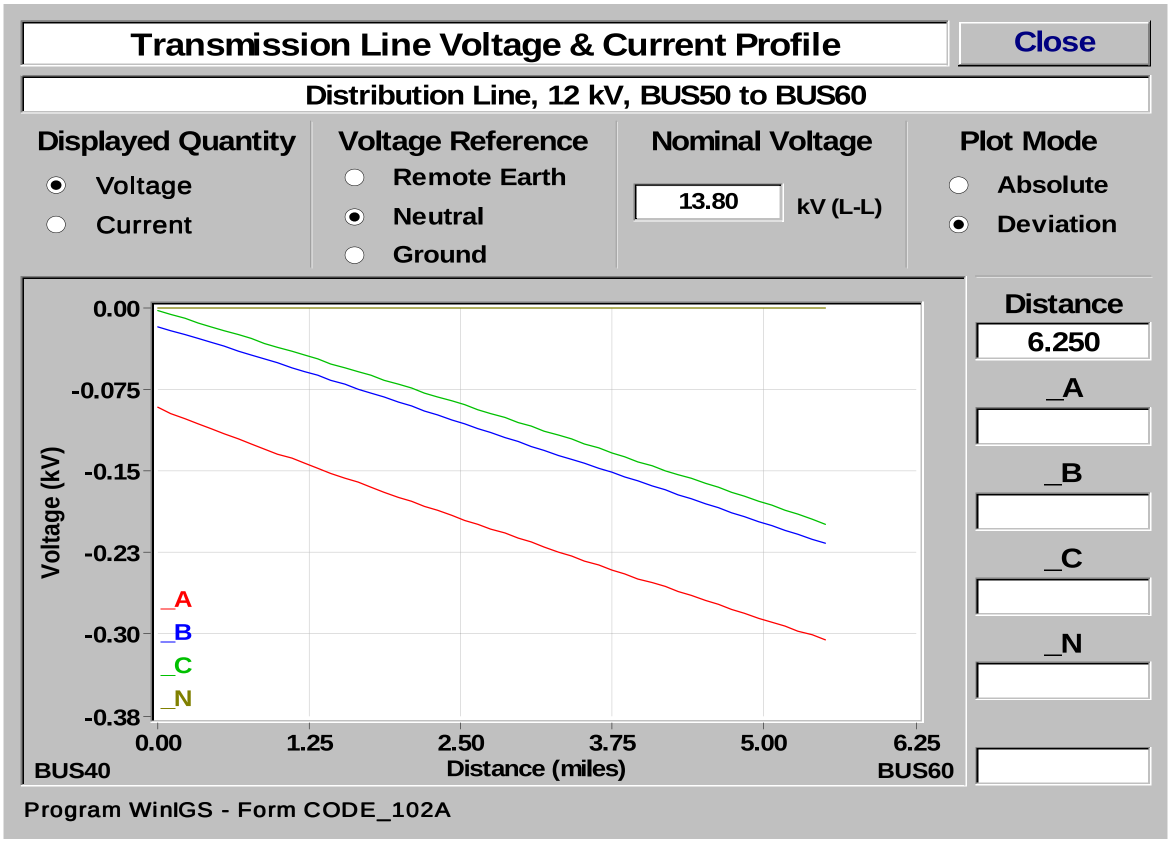


Figure B2.14. Voltage Profile of a Typical Customer System with One Microsource Operated at Unity Power Factor

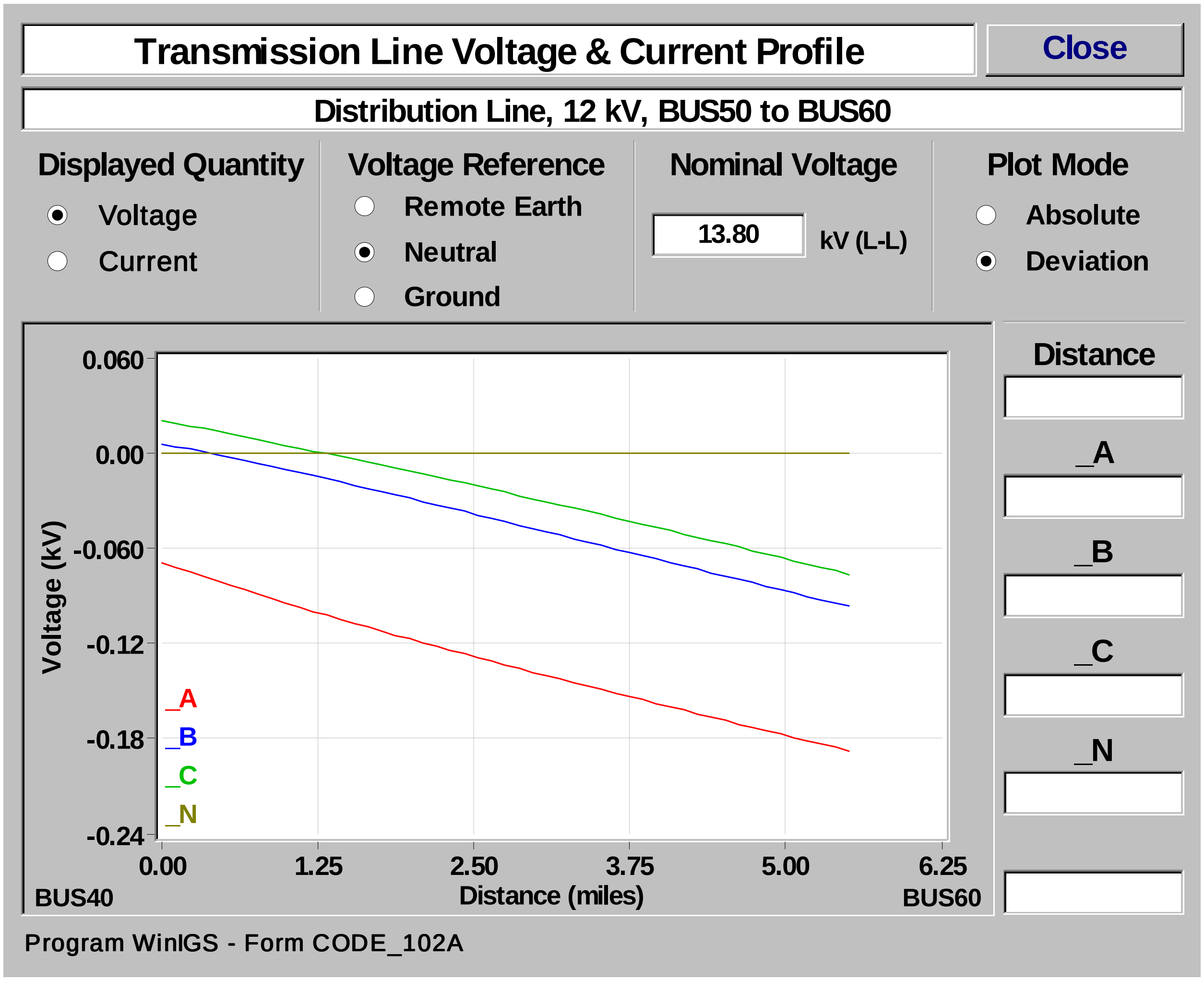


Figure B2.15. Voltage Profile in a Typical Customer System with One Microsource Operated at 0.95 (Current Leading) Power Factor

B2.5 Electromagnetic Interference

This section discusses electromagnetic fields (EMFs) in typical distribution systems and the factors that affect EMF levels. Specific system arrangements that may lead to increased EMFs and interference are described along with traditional methods and possible uses of DER to mitigate EMFs.

Any circuit that carries electric current will generate a magnetic and electric field. The effects of EMFs on humans have been controversial. The IEEE has taken the position that “prudent avoidance” is appropriate for EMFs. It is undeniable that the effect of EMFs on the performance of electrical equipment is often undesirable. For example, EMFs may cause CRT displays to flicker, interfere with the operation of pacemakers, and affect the current distribution in other circuits, leading to local overheating. These effects can be addressed as pure engineering problems. The possibility of MicroGrids offers an opportunity to rethink these issues and to establish good engineering practices for MicroGrid design.

EMF Sources

Electrical field sources are the voltages of the various conductors on circuits. Magnetic field sources are the electric currents that flow in the various conductors on circuits. Because of low operating voltage, the electric fields are low and are not considered to be significant. Electric currents are high and have the potential of generating high magnetic fields with undesirable effects.

EMFs in MicroGrids are illustrated in the figures below. A simplified customer system is shown in Figure B2.16: The system consists of two identical 208-V (line-to-line) circuits; one circuit is enclosed in aluminum conduit and the other in steel conduit of same nominal diameter. Figures B2.17 and B2.18 illustrate the magnetic field around each of the circuits at the same distance from the circuit center. Note that the magnetic field around the circuit enclosed in steel conduit is much lower (peak value of 76 milligauss) than the magnetic field around the circuit enclosed in the aluminum conduit (peak value of 365 milligauss).

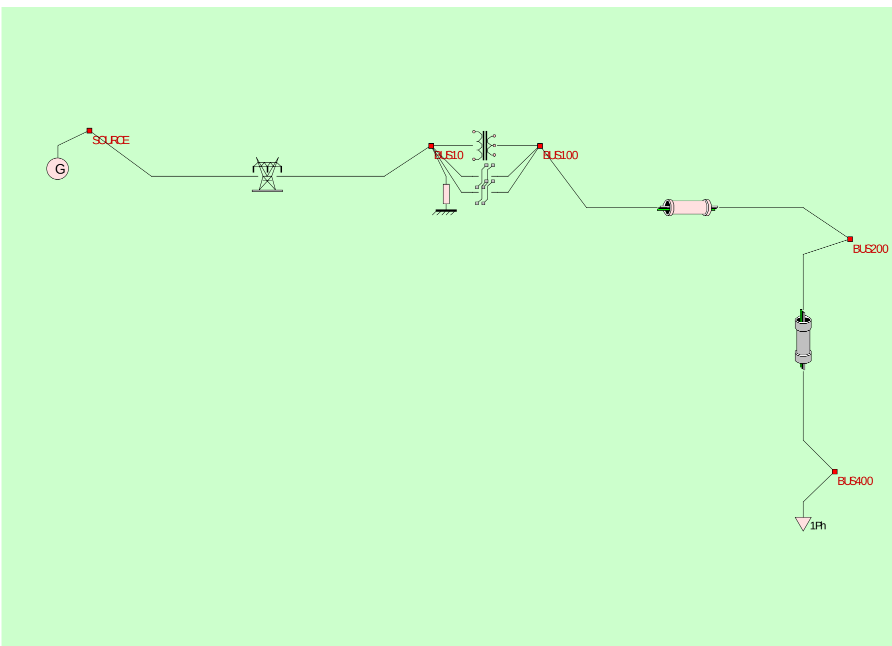


Figure B2.16 Illustration of a Distribution System in Steel and Aluminum Conduits

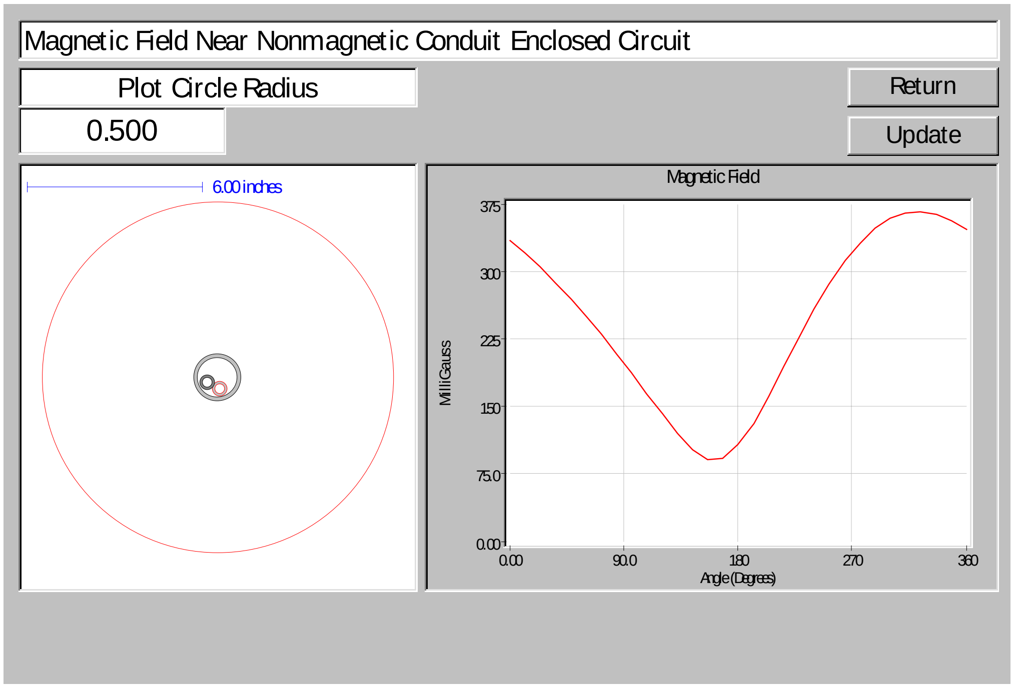


Figure B2.17 Illustration of the Magnetic Field Around the Circuit of Figure B2.16 Enclosed in Aluminum Conduit

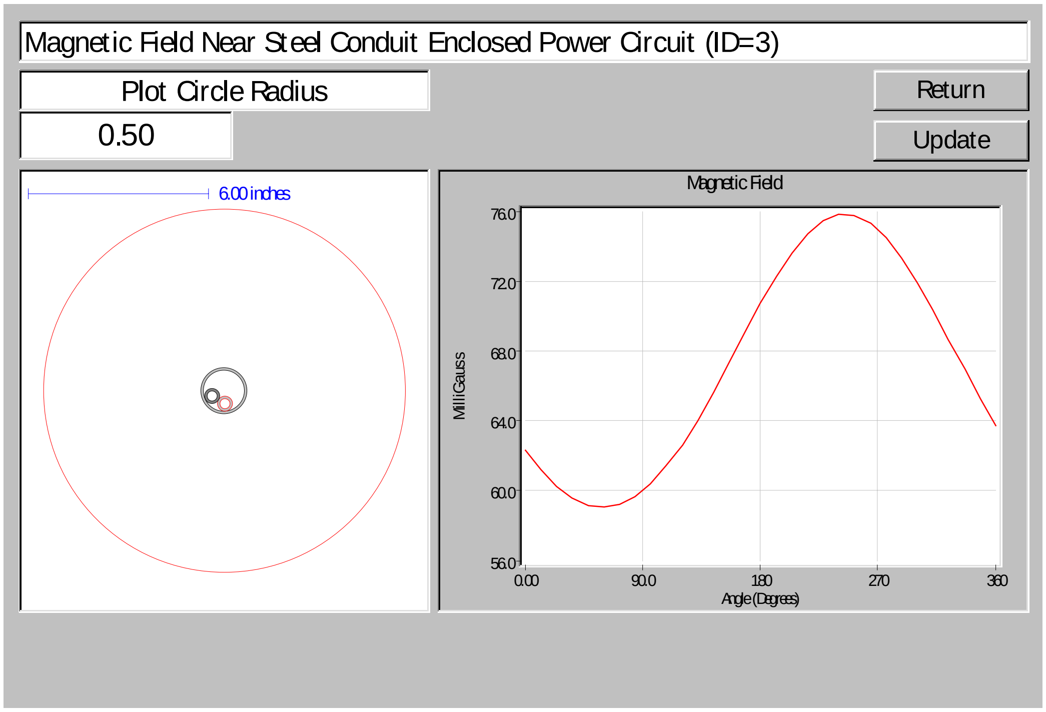


Figure B2.18 Illustration of the Magnetic Field Around the Circuit of Figure B2.16 Enclosed in Steel Conduit

Effects of DER on EMFs

Electromagnetic fields exist in any electric power distribution circuit. The level of the EMFs depends on the imbalance of the system and the geometry of the circuit conductors. The geometry of the circuit conductors can be controlled by the use of conduit that tends to put all the conductors close together so that the magnetic fields are minimized. The beneficial effects of DER can come from use of converter controls to minimize circuit imbalances.

APPENDIX C. Environmental Issues Related to MicroGrids

Although moving power generation closer to load creates opportunities for economic gain through higher reliability and use of waste heat, it raises serious environmental concerns. Moving power generation from large, easily monitored, and (usually) remote generating stations to smaller scale, difficult-to-monitor generation sites close to population concentrations is likely to increase human exposure to pollutants and noise. Other drawbacks are the dangers inherent in combustion at high pressures close to occupied spaces, and the problems of delivery and installation of equipment in occupied buildings.

The technologies that may be used in MicroGrids have diverse environmental characteristics. Some, notably PV systems, will have few environmental impacts at the point of generation; others, particularly diesel reciprocating engine generators, which are already numerous, can be quite damaging to the environment.

Air Quality

Given the serious air quality problems in many urban areas of the U.S., the prospect of thousands or hundreds of thousands of DER; particularly combustion devices, being installed in densely populated areas is cause for concern. High levels of ozone, particulate matter less than µm in diameter (PM-10), and carbon monoxide (CO) are among the largest contributors to current U.S. air quality problems. This section summarizes the impacts that MicroGrid technologies are likely to have on air quality.

Ozone levels are directly linked to ozone's precursor pollutants, reactive organic gas (ROG) and nitrogen oxide (NOx). Nationally, the two largest source categories for volatile organic compound (VOC) emissions are industrial processes and transportation. NOx emissions are mainly a consequence of combustion processes. Some fuels, notably coal, contain nitrogen that is oxidized during combustion. However even fuels that contain no nitrogen emit NOx because it is formed from nitrogen and oxygen in the air in systems with high combustion temperatures. Nationally, the two biggest sources of NOx are electric power generating plants and highway vehicles. Gas turbines, reciprocating engines, and reformers all involve high temperatures that result in NOx production. Microturbines and fuel cells have much lower NOx emissions because of their lower combustion temperatures.

Ozone tends to peak in late spring and into summer as temperatures warm. Because of lengthy reaction times, peak ozone concentrations frequently occur significantly downwind of source areas. Ozone tends to concentrate in densely populated areas, so high levels can occur at considerable distances downwind of urban centers. Overexposure to high levels of ozone can result in shortness of breath and other respiratory problems, including aggravated asthma symptoms, chest pain, coughing, and possible chronic lung damage. It is therefore important to focus on ozone characteristics in considering the effects of DER systems.

PM-10 consists primarily of soot, dust, smoke, fumes, or mists and is a growing health concern. Major sources of PM-10 include motor vehicles, wood-burning stoves and fireplaces, construction, landfills, agriculture, wind fires, windblown soil, and industrial sources. Under

EPA legislation, the 24-hour PM-10 standard is a maximum concentration of 150 $\mu g/m^3$. PM-10 dominates in summer and fall as a result of arid soils that winds and agricultural activity stir into the ambient air. Enhanced levels of particulate matter can bring on asthma attacks and bronchitis and can cause premature death in people with cardiac or respiratory disease. Among DER technologies, diesel reciprocating engines raise the largest PM-10 concern; microturbines and fuel cell generate minimal levels of PM-10.

Carbon monoxide (CO) is the result of incomplete fuel combustion. It is a byproduct of motor vehicle exhaust, which contributes more than two-thirds of all CO emissions in the U.S. In general, CO emissions in the U.S. are considerably less severe than ozone or PM concentrations. Because CO originates mainly from automobile exhaust, improved regulations leading to cleaner burning fuels have significantly reduced CO emissions. High levels of carbon monoxide exposure are believed to affect the central and nervous system, depriving the body of oxygen and potentially contributing to cardiovascular disease. CO can result from all combustion processes, but controlled lean combustion used for power generation does not usually produce CO unless equipment is malfunctioning. However, because DER equipment might well be running in enclosed spaces that might result in CO buildup, CO risks must be taken seriously in MicroGrid planning and design.

Environmental Impacts Estimate for a Microturbine

Below are rough estimates of emissions from a small, newly installed microturbine. Calculations are based on the characteristics of a 30-kW Capstone microturbine.
Technical specifications for this product estimate NOx emissions of approximately 6.7 g/hr or 58.7 kg/yr if the generator runs year round at an output of 28 kW generating 245 MWh), which translates to 0.24 G/kWh. This figure corresponds to an exhaust gas concentration of less than 9 ppmv, comparable a small amount more than the emissions of three cars in the state of California in 2000. This emissions rate is comparable to that of central station generation. The estimated amount of CO emitted from a microturbine is just over 100 kg/yr, which is equivalent to only a fraction of one car.

Reducing pollutants from combustion technologies

Modifications to reduce pollutant emissions from reciprocating engines include incorporating: precise controls for air-to-fuel ratios, lean-burn combustion techniques, electronic ignition, exhaust gas recirculation, wet controls, and fuel conditioning. Combustion modifications for gas turbines include incorporating wet controls, lean pre-mix, and catalytic converters. Common drawbacks of these modifications are increased cost, reduced efficiency, and a potential increase in emissions of other pollutants.

Post-combustion technologies for engines and turbines include selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR). For engines, catalytic converters and oxidation catalysts are used to eliminate pollution emissions. Diesel engines may use particulate traps, oxidation catalysts, NOx absorbers, and lean-NOx catalytic converters to clean emissions. Technologies are currently being developed that substantially reduce NOx and CO emissions from gas turbines; however, further efforts are needed to bring these technologies from the demonstration phase to commercial production.

Table C.1 shows estimates of emission rates for common existing distributed generating technologies and for technologies likely to be developed during the next decade.

Present-Day Air Emissions Factors (g/kWh)

	NOx	CO	PM
Fuel Cell			
250 kW	**N/A**	**N/A**	**N/A**
Microturbine			
75 kW	**0.24**	**0.24**	**N/A**
Diesel Back-up			
7.5 kW	**8.17**	**3.26**	**0.54**
500 kW	**8.57**	**0.54**	**0.16**
Gas Back-up			
55 kW	**6.05**	**N/A**	**N/A**
500 kW	**25.29**	**5.66**	**N/A**

Table C.1. DER Technology Emissions Rates in g/kWh

As Table C.1 shows, current estimates of emissions rates vary widely, but it is clear that the technologies incorporated in a MicroGrid will have a significant impact on MicroGrid emissions. A key public policy question is how to encourage use of technologies with fewer environmental consequences. The emissions rates shown are for uncontrolled equipment; the environmental performance of MicroGrids can be considerably improved through application of the various emissions control technologies noted above, which will likely be required in many jurisdictions. The control technologies appropriate for reducing emissions, e.g. catalytic converters, are familiar and well developed for mobile applications, so there are no significant technical barriers to their deployment in MicroGrids. The regulatory situation, however, is more complex, as described below.

Air Pollutant Transport

In areas with serious air quality problems, air transport from one region to another is an important environmental issue. Pollutant transport from the San Francisco Bay Area to the Central Valley is an example that shows the importance of considering air quality conditions and flow patterns from adjoining air basins. A 1990 study by the California Air Resources Board (ARB) investigated ozone and ozone precursor transport to the Central Valley in California. The 1983-1986 assessment concluded that approximately 43 percent of ozone exceedance days in California’s central valley were significantly affected by upstream wind flow patterns from the San Francisco area .

Air Pollution Regulations and DER

The federal government, through the EPA, sets pollution standards and oversees state and local behavior, enforcing programs related to motor vehicle emissions, fuels, and smog checks. State or local air quality authorities develop and implement control measures for stationary sources such as factories and plants. Regulations for generator sources focus mainly on larger scale operations, but DER are considered point sources and are accordingly subject to regulation by the appropriate authority. In many jurisdictions, permit conditions for currently assume that small-scale generators will only be used in emergencies, so permit conditions are written accordingly. The prospect of regulating distributed generation technologies is complex because regulatory agencies that control emissions within each air district are concerned with improving air quality within their own regions. Displacing larger generators from the grid and replacing them with local generators will influence air quality in many localities, so there could be resistance from local air quality agencies. The possible increased local emissions resulting from a nearby DER source would likely be considered problematic by the local agency despite the tradeoff of potential reduced emissions outside the local area.

Surveys of DER installation sites have found that the most challenging aspects of the sitting and permitting process were the paperwork, regulatory interpretation process, and annual testing procedures involved with obtaining an air pollution permit. The most costly aspects of environmental controls were on-site testing (if required) along with legal and engineering fees. The permit process should be standardized to make it less time consuming. The process could be streamlined if certain equipment could be pre-qualified as meeting an acceptable minimum standard.

Noise

Noise pollution is primarily an issue associated with road, highway, or building construction; industrial processes; airplanes; and vehicles in heavily traveled areas. As a result, regulations tend to focus on industrial and traffic noise.

Some example typical noise levels are 50 dBA for quiet urban daytime, 25 dBA for a quiet rural nighttime, 60 dBA for heavy traffic at a distance of 90 m, and nearly 100 dBA for a gas lawn mover at 1m.

Some states that regulate noise levels from industrial operations are Oregon, Hawaii, Delaware, and Maryland. In Oregon, the maximum allowable noise level for industrial sources is 60 dBA. Hawaii, Minnesota, and Maryland all have a maximum permissible sound level of 70 dBA for industrial activities, and New Jersey and Delaware cap these noise levels at 65 dBA.

The Federal Highway Administration Regulations constitute the Federal Noise Standard, which states that noise abatement measures must be taken when noise levels for highway construction approach or exceed the Noise Abatement Criteria (NAC). The NAC for residences, motels, hotels, schools, churches, hospitals, and libraries specify a maximum interior level of 52 dBA. For comparable exterior situations, the NAC level is 67 dBA. For quiet lands whose serenity and low noise level are considered essential, the NAC level is 57 dB.
A 25- to 30-kW microturbine installation produces an approximate noise level of 65 dBA at 10 m. Noise level increases/decreases by approximately 6 dBA for each halving/doubling of

distance away from the sound source. This means that a properly functioning microturbine could, theoretically, be heard up to a distance of more than 10 km. Realistically, however, this noise would not carry such a great distance under normal outdoor conditions. Using the rule of thumb, sound levels would be about 53 dBA 40 m away from the source and only 35 dBA 320 m away. This 35 dBA is almost comparable to the noise level in a quiet nighttime rural location, virtually unnoticeable for outdoor conditions. This example indicates that noise concerns can easily be avoided when DER are deployed.

Conclusions

The environmental issues raised by DER are significant and need to be addressed. Regulations or incentives should be created to encourage adoption of the more environmentally benign DER technologies. With local air pollution control districts focused primarily on air quality conditions within their jurisdictions, adoption of DER could be stymied by local concerns even though a DER installation might be less polluting than the central station energy production that it displaces, reducing emissions overall in the wider geographic area served by the central station. In addition, the local/regional effects of smog on dense populations suggest that total human exposure could be worse with DER in place even if total emissions are lowered.

All of the possible environmental impacts of DER can be mitigated to some extent. Air emissions can be reduced by choosing low-emission technologies, limiting hours of operation, modifying combustion, or incorporating post-combustion treatment. Noise and vibration problems can be addressed by installing generation equipment on shock-isolated pads and in enclosures. Silencing equipment for exhaust is available for turbines and engines. In general, noise abatement techniques have worked for microsources, and noise has not caused siting problems in residential and commercial areas, but wider deployment of DER could result in stronger opposition from neighbors .

With the increased interest in distributed generation resources, the current regulatory status for DER deployment is changing quickly and the need to address environmental issues is becoming more critical in establishing a context of a controlled DER environment.